DEPARTMENT OF COMMERCE

TECHNOLOGIC PAPERS

OF THE

BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 207

MANUFACTURE AND PROPERTIES OF STEEL PLATES CONTAINING ZIRCONIUM AND OTHER ELEMENTS

BY

GEORGE K. BURGESS, Physicist
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Bureau of Standards

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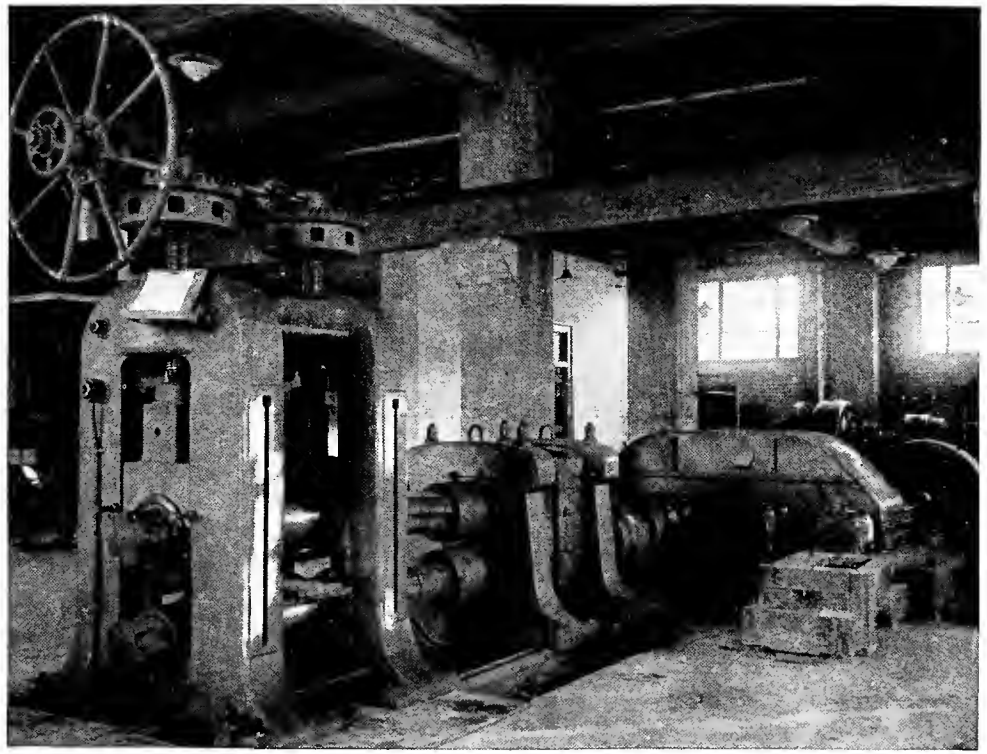


FIG. 1.—*Two high 16-inch plate mill (of the Bureau of Standards) in which the ingots were rolled*

MANUFACTURE AND PROPERTIES OF STEEL PLATES CONTAINING ZIRCONIUM AND OTHER ELEMENTS

By George K. Burgess and Raymond W. Woodward

ABSTRACT

This paper describes the manufacture and certain physical properties obtained from steel plates produced from about 193 heats of steel containing in various combinations the following principal variable elements: Carbon, silicon, nickel, aluminum, titanium, zirconium, cerium, boron, copper, cobalt, uranium, molybdenum, chromium, and tungsten.

None of the steels presented any difficulties in rolling into plate except those containing boron. Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron, which is fusible at the temperatures ordinarily used in rolling, but at slightly lower temperatures steel containing boron can be rolled successfully.

The usual mechanical and impact tests were carried out on all of the steels. It is shown that steel containing 0.40 to 0.50 per cent carbon, 1 to 1.50 per cent silicon, 3 to 3.25 per cent nickel, and 0.60 to 0.80 manganese and deoxidized with a simple deoxidizer, such as aluminum, can be produced having a tensile strength of approximately 300 000 lbs./in.^{2} with excellent ductility and toughness. This type of steel is recommended for a structural material.

Although the same high properties are obtained in steels of the above composition with the aid of additional elements, it does not appear necessary in general, to resort to such additions of more costly alloying elements.

CONTENTS

I. INTRODUCTION

This investigation originated in the need of the ordnance departments of the Army and Navy for information regarding the effects on the ballistic properties of light armor plate of certain chemical elements, such as zirconium, on the one hand, and the effects of such elements as uranium in reducing erosion in guns, on the other hand. The account here given relates mainly to the efforts to produce armor plate of various compositions.

After conference with the representatives of the several establishments interested, a joint program was outlined according to which the Bureau of Mines was to produce and analyze ingots of the desired compositions, the Bureau of Standards to manufacture and heat treat plates, carry out physical tests, microexaminations and chemical analyses, and develop methods of chemical analysis when needed for the more unusual elements in steel, and the Navy Department was to carry out the ballistic tests.

The most urgent problem was the determination of the effect of zirconium on the properties of carbon steels and of nickel-carbon steels, and especially to differentiate between the effects of zirconium and silicon.

As the work progressed it was considered desirable to investigate the effects of other elements, and there were accordingly included steels containing titanium, aluminum, boron, molybdenum, cerium, cobalt, chromium, vanadium, tungsten, uranium, and copper.

In addition to the ingots furnished by Dr. Gillett, opportunity was given to examine plates of steel containing zirconium manufactured by an automobile manufacturer.

Although the results of the ballistic tests are not available for publication, an account of the mechanical properties and tests of this series of somewhat unusual steels is considered worthy of consideration. The nickel-silicon group appears to be of particular interest, as is also the fact brought out that zirconium does not appear to confer any especially advantageous properties to types of steel here studied, and, in fact, behaves very much like silicon, although for carbon steels the data are not sufficiently complete to warrant conclusions.

The investigation throws some additional light on the manner in which certain of the rarer elements enter into steel, and there were also developed new analytical methods for the determination of zirconium in steels and of several of the unusual elements in the presence of each other.

II. COMPOSITION OF INGOTS

The chemical composition of all ingots was determined from drillings taken from both the top and bottom of the ingots. From each of these sets of drillings an analysis was made for all the elements occurring in the steel by Dr. Gillett and his associates at Ithaca. Samples were also taken from the top and bottom crops at the Bureau of Standards and further analysis made for the aluminum, titanium, and zirconium content.[1] Since the exact determination of this combination of elements presents some difficulty, the method used at the Bureau is included in the appendix.[2]

The composition of the various ingots will be found in Tables 11 to 22, while Table 1 gives a list showing in which table the data for a given heat appears. The analytical values for carbon, silicon, manganese, nickel, and other alloying elements are as reported by Dr. Gillett. Those for aluminum, titanium, and zirconium are a weighted mean of the determinations made at the Bureau of Standards and by the Bureau of Mines. In case the top and bottom samples showed segregation to have occurred in the ingot the values for both top and bottom are given in the table. No determinations were made of the sulphur or phosphorus content except in the few cases noted, since the steels were made from Armco iron as a base, and it is believed that these steels will run below 0.035 per cent sulphur, except 1256 and 1257, in which it was intentionally raised, and below 0.015 per cent phosphorus.

[1] These determinations were made under the direction of Dr. G. E. F. Lundell.

[2] See also Lundell and Knowles, Jl. Ind. and Eng. Chem., 12, p. 562, 1920; The determination of zirconium in steel.

In addition all will contain about 0.04 per cent copper and probably a small amount of cobalt, carried in by the commercial nickel, in the steels containing nickel.

TABLE 1.—List Showing Tables in Which Composition and Mechanical Properties of Various Heats May be Found

Heat No.	Table No.	Heat No.	Table No.	Heat No.	Table No.	Heat No.	Table No.	Heat No.	Table No.
1101	13	1163	11	1204	12	1243	14	1290	14
1102	11	1164	11	1205	12	1244	22	1291	14
1103	13	1165	12	1206	12	1245	12	1292	14
1104	11	1166	12	1207	20	1246	12	1293	14
1105	13	1167	12	1208	12	1247	14		
1106	13	1168	12	1209	12	1248	14	Comparison steels	
1107	13	1169	12	1210	14	1249	14		
1109	13	1170	12	1211	14	1250	14		
1111	14	1171	12	1212	14	1251	12		
1112	14	1172	12	1213	14	1252	15	1	14
								2	14
1113	12	1173	20	1214	12	1253	15	3	18-21
1114	12	1174	12	1215	12	1256	15	4	18
1115	14	1175	14	1216	12	1257	15	5	19
1117	14	1176	14	1217	12	1258	15		
1118	12	1177	22	1218	14	1259	15	6	18
								7	14
1119	14	1178	22	1219	14	1260	15	8	14
1120	12	1180	13	1220	14	1261	17	9	18
1128	12	1181	13	1221	14	1263	17	10	14
1129	12	1182	13	1222	14	1264	17		
1130	12	1183	13	1223	14	1267	17	11	14–18
								12	19
1131	14	1184	13	1224	14	1268	15	13	12
1132	14	1185	13	1225	14	1269	11	14	14–21
1133	14	1186	14	1226	12	1270	11	15	18–21
1134	14	1187	14	1227	12	1271	20		
1135	18	1188	14	1228	22	1272	15	16	14
								17	14
1136	18	1189	14	1229	22	1273	20	18	14
1138	14	1190	14	1230	14	1274	17	19	19
1144	14	1191	14	1231	14	1275	17	20	14
1145	14	1192	14	1232	14	1276	17		
1146	14	1193	14	1233	14	1277	17	21	14
								22	21
1147	12	1194	14	1234	14	1278	17	23	20
1155	19	1195	14	1235	14	1279	16	24	14
1156	19	1196	14	1236	12	1280	16	25	14
1157	14	1197	14	1237	12	1281	15–16		
1158	14	1198	11	1238	12	1282	16	26	14
								27	14
1159	14	1199	11	1239	12	1283	16	28	12
1160	14	1200	11	1240	14	1285	16		
1161	14	1201	11	1241	14	1286	16		
1162	14	1202	12	1242	12	1289	14		

III. PREPARATION OF PLATES AND TEST PIECES

1. CROPPING AND ROLLING OF INGOTS

The ingots after having been made at the Bureau of Mines Experimental Station at Ithaca, N. Y., as described in a forthcoming paper of the Bureau of Mines, were shipped to the Bureau of Standards and there rolled into plates.

(a) DESCRIPTION OF INGOTS

The first ingots received were plain, round ingots without hot tops, cast large end up, the length being about 15 inches, top diameter about 3½ inches, and bottom diameter about 2½ inches.

This series, embracing Nos. 1101 to 1120, naturally contained a large pipe or cavity at the upper end, and a top crop of about 5 inches was necessary to remove physically unsound material.

Bottom crops on this series (except Nos. 1118 and 1120) had been taken previous to receipt at the Bureau of Standards. No crops were taken on ingot Nos. 1101–1104, 1109, 1111, and 1114 at the Bureau, as these ingots had been machined down on the ends and surface before shipment.

Ingots from No. 1128 to 1158 were also of the same general dimensions and form as the previous ones, but with the addition of a hot top of about 2¼ inches diameter. Most of this top had been knocked off while the ingot was still hot, directly after stripping from the mold. The tops of these ingots were cropped just below the junction of the hot top with the body of the ingot, or slightly farther in a few cases, to insure sound material. The bottom crop was just sufficient to remove the rounded end of the ingot.

The remainder of the ingots were square in cross section, about 3 inches at the top and 2½ inches at the bottom. The length, exclusive of the hot tops, was about 21 inches. The average weight of these ingots was 41.5 pounds before cropping and 35 pounds when ready to roll. The length after cropping was about 18 inches.

Table 2 gives a summary of the weight of ingots and crops for the various types of the ingots and also the percentage available for rolling after having been cropped. The data show remarkably well the advantage to be gained by the use of a hot top, the available material without such means being about 65 per cent, while with a hot top the average was 84 per cent. This latter figure should be slightly reduced (possibly 5 per cent) to allow for a portion of the hot top having been knocked off at Ithaca. This corrected figure, however, agrees very well with similar data obtained on 4½-ton ingots and reported elsewhere,[3] especially when the small size of the ingots used in this investigation is considered.

(b) ROLLING DATA

The ingots were rolled in a two-high 16-inch plate mill, a photograph of which is shown in Fig. 1. This mill is driven by a 150-horsepower 230-volt direct-current motor and is nonreversing.

[3] Steel Rails from Sink-Head and Ordinary Rail Ingots, by George K. Burgess, Bureau of Standards Technologic Paper, No. 178.

The motor speed is variable from 250 to 1000 revolutions per minute, which with the reduction gear gives a roll speed of 20 to 80 revolutions per minute. For this work the roll speed was kept constant at the lowest value, corresponding to a peripheral velocity of approximately 83 feet per minute.

The heating of the ingots was by means of a gas-fired semi-muffle furnace. Usually about 10 ingots were rolled at one heating, and they were charged into the cold furnace and brought to temperature with the furnace. With the exception of those steels containing boron, which are discussed later, the furnace temperature was maintained at from 1100 to 1150° C. The ingots were rolled until their temperature had fallen to about 850° C. This temperature was checked in many cases by means of an optical pyrometer. The ingots were then reheated and the operation repeated.

All of the ingots were first squared down to 2½ inches square in four passes by turning the ingot through a 90° angle at alternate passes. This gave a maximum reduction of about 10 per cent per pass.

Ingots up to 1163 were then cross rolled until 6 to 7 inches wide and then rolled lengthwise until ½ inch thick. The average size of finished plate was about 28 by 6½ by ½ inch. A total of about 40 passes was required, with about 5 per cent reduction per pass. The other ingots were entirely cross rolled after squaring, producing plates of various sizes, usually about 20 by 13 by ½ inch (or ⅜ inch).

It is probable that the percentage reductions per pass could be considerably increased, but since the rolling properties of the majority of the ingots were unknown it was deemed advisable to have a considerable margin of safety. A portion of those ingots which were rolled into long narrow plates (1101 to 1162) was cut off and rerolled to ⅜ inch thickness.

TABLE 2.—Average Ingot Weights

Ingot Nos.	Original weight	Top crop	Bottom crop	Cropped ingot	Available for rolling	Loss in rolling
	Pounds	Pounds	Pounds	Pounds	Per cent	Per cent
1101–1120	34.5	12.0	.....	21.2	64.9	3.1
1128–1158	34.5	5.9	1.5	27.1	79.8	2.3
1159–1293	41.5	4.8	1.8	35.0	84.2	1.9
Average of all	40.5	5.3	1.7	32.7	82.4	2.0

(c) DISPOSITION OF MATERIAL

The plates from ingots 1101 to 1162 were sawed similar to sketch of Fig. 2, which represents plate No. 1129, although typical of all. *AB* and *GF* were plates for ballistic tests, *BC* and *CD*

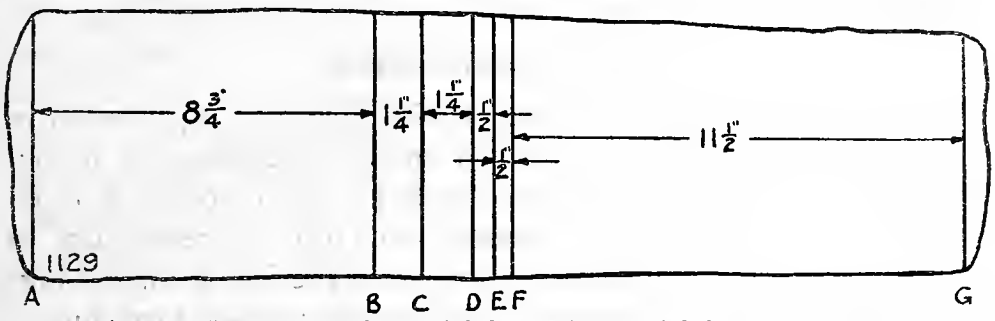


FIG. 2.—*Disposition of material from plates rolled from small ingots*

each about 1 inch wide, were for tensile specimens, *EF* for microscopic examination and thermal analyses, while the remaining small pieces were held in reserve. The lengths of the two plates were so adjusted that the rerolled portion would be the same length as the unrolled portion.

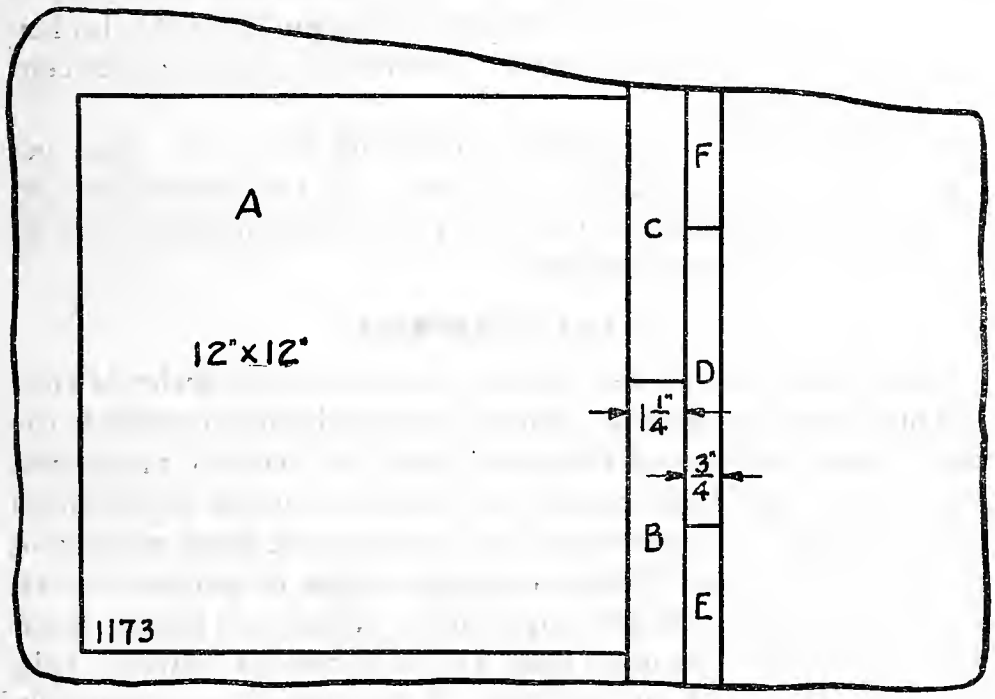


FIG. 3.—*Disposition of material from plates rolled from large ingots*

From the later plates (1163 to 1293) a single ballistic test piece was cut 12 by 12 inches, or as large as possible, if the ingot was too small to permit of this dimension. The other test pieces were taken then as shown by the typical diagram for plate No. 1173 in Fig. 3. *A* is the ballistic plate, *B* and *C* tensile specimens,

D for impact sample, and *E* and *F* for microscopic examination and thermal analyses, respectively. Any plates which were not perfectly flat were straightened at a temperature of about 800° C by means of a hydraulic forging press. The plates were not pickled until after heat treatment.

(d) INGOTS CONTAINING BORON

As was anticipated, considerable difficulty was experienced in rolling the ingots containing even small percentages of boron. Ingots Nos. 1254 (0.73 per cent B) and 1255 (0.30 per cent B) were heated in the ordinary manner to 1100° C preparatory to rolling. Upon removing these ingots from the furnace with tongs they fell apart under their own overhanging weight, furnishing a striking example of hot-shortness. No. 1262, containing 0.46 per cent boron, was heated to only 960° C and likewise broke after partial rolling. Nos. 1261, 1263, and 1264 were similarly heated and were rolled satisfactorily, although containing 0.71, 0.23, and 0.46 per cent boron, respectively. Nos. 1265 and 1266 were partially rolled, but broke up under the rolls and, in fact, were so hard to roll that two of the coupling collars of the mill were also broken at the same time. These ingots contained 0.23 and 0.46 per cent boron, respectively.

No difficulty was encountered in rolling Nos. 1267 (0.44 per cent B), 1274, 1275, 1276, 1277, and 1278 (all containing 0.10 per cent B), although Nos. 1274 and 1276 showed numerous cracks and fissures in the finished plates.

2. HEAT TREATMENT

In determining the mechanical properties of the series of steel two needs were considered. First, it was desirable to correlate the mechanical properties of the steels with their ballistic properties; and, second, the large number of steels of varying composition made available an opportunity for studying the effect of some of the more uncommon alloying elements on the properties of steel. To satisfy properly the first requirement, tensile and impact specimens should be prepared from the heat-treated plates. This, however, because of the hardness of the plates, was practically impossible to carry out without what seemed to be unwarranted expense and time. For the second requirement it would be preferable to make tests on a series of specimens from each composition drawn back to various temperatures after quenching from the proper temperature. This, again, would have required con-

siderable additional work; and, moreover, there was not enough material to make a complete survey of the entire tempering range.

A compromise was accordingly effected whereby tensile tests were made on normalized and heat-treated specimens cut from the plates before heat treatment, as noted in Section III, 1 (*c*). The heat treatments were similar for all compositions of the series. That is, after normalizing and quenching in oil each from a temperature 30° C above the end of the upper critical range the specimens were drawn back at a temperature 175° C for three hours, this being the same treatment given the plates for ballistic testing.

TABLE 3.—Normalizing and Hardening Temperatures

[All temperatures in ° C]

No.	Temp.	No.	Temp.	No.	Temp.	No.	Temp.	No.	Temp.
1101	840	1159	780	1195	840	1231	800	1271	780
1102	860	1160	780	1196	860	1232	780	1272	820
1103	825	1161	840	1197	860	1233	780	1273	820
1104	840	1162	780	1198	900	1234	840	1274	820
1105	810	1163	860	1199	900	1235	860	1275	840
1106	860	1164	860	1200	820	1236	840	1276	760
1107	860	1165	820	1201	840	1237	840	1277	800
1109	800	1166	860	1202	860	1238	800	1278	850
1111	770	1167	780	1204	840	1239	800	1279	760
1112	790	1168	840	1205	820	1240	800	1280	780
1113	770	1169	820	1206	820	1241	780	1281	780
1114	770	1170	780	1207	800	1242	800	1282	800
1115	780	1171	860	1208	800	1243	800	1283	780
1117	800	1172	860	1209	800	1244	820	1285	820
1118	785	1173	840	1210	860	1245	820	1286	800
1119	810	1174	840	1211	860	1246	800	1289	800
1120	820	1175	840	1212	800	1247	840	1290	820
1128	820	1176	820	1213	800	1248	880	1291	780
1129	840	1177	860	1214	820	1249	800	1292	780
1130	820	1178	860	1215	800	1250	920	1293	800
1131	830	1180	860	1216	820	1251	820		
1132	830	1181	860	1217	800	1252	800		
1133	820	1182	860	1218	820	1253	805		
1134	820	1183	860	1219	820	1256	840		
1135	780	1184	900	1220	800	1257	840		
1136	780	1185	900	1221	820	1258	780		
1138	805	1186	900	1222	780	1259	780		
1144	820	1187	900	1223	780	1260	820		
1145	820	1188	900	1224	820	1261	880		
1146	780	1189	900	1225	820	1263	880		
1147	790	1190	860	1226	840	1264	820		
1155	805	1191	860	1227	840	1267	880		
1156	805	1192	860	1228	800	1268	840		
1157	810	1193	860	1229	820	1269	840		
1158	780	1194	840	1230	760	1270	840		

The normalizing and hardening treatments for the small-test specimens were carried out in a small electric muffle furnace; the specimens were placed in the cold furnace, brought to the desired temperature with the furnace, and held at that temperature for 15 minutes. The normalized specimens were

allowed to cool in the air, and the specimens to be hardened were quenched in the oil at room temperature. In Table 3 are given the common normalizing and quenching temperatures. For tempering, the specimens were heated in an oil bath to 175° for three hours and allowed to cool in the air after removing from the bath.

The duplicate tensile specimens from each plate were, in general, normalized at the same time, and then one of them hardened and tempered and the other kept in the normalized condition.

The ballistic plates were heat treated in a manner similar to that used for the test specimens, except that larger furnace units were required and the plates were held at the desired temperatures for 45 minutes before withdrawing from the furnace.

IV. PROPERTIES OF THE MATERIAL

1. CRITICAL RANGES

In order to prescribe properly the heat treatment of the various steels, the critical ranges of several of them were determined, particularly those containing the more unusual elements, such as zirconium, boron, cerium, copper, and large amounts of silicon. Inverse rate curves were obtained on samples of 1.5 to 2.0 grams mass by means of a modified Rosenhain furnace.[4]

The temperature measurements were taken with a platinum, 90-platinum 10-rhodium thermocouple. The rate of heating and cooling was approximately 0.20° C per second, while the maximum temperature to which the specimen was carried varied between 840 and 920° C.

Table 4 gives the results obtained, together with the composition of the materials investigated. Although the end of the Ac_{2-3} transformation is all that is needed to determine the proper heat treatment, the other values are included as a matter of interest. For comparison there are also shown in the table data for a plain carbon and a 3 per cent nickel steel, both of which contain the other elements within commercial limits.

[4] Scott and Freeman, Bull. Am. Inst. of Min. and Met. Eng., No. 152, p. 1429; August, 1919. Also Bureau of Standards Scientific Paper, No. 348.

TABLE 4.—Critical Ranges of Representative Material

[All temperatures in ° C]

No.	Composition								Ac_1			Ac_{2-3}		Ar_{3-2}		Ar_1		
	C	Si	Mn	Ni	Al	Ti	Zr	Other elements	Beg.	Max.	End	Max.	End	Beg.	Max.	Beg.	Max.	End
1101	0.51	1.15	0.80	.....	0.09	0.04	0.10	.....	755	759	778	.....	780	745	716	695	690	678
1102	.36	1.15	.65	.....	.03	.06	.....	.....	750	754	770	.....	842?	784	755	684	677	668
1104	.39	.66	.58	.....	.01	.03	.....	.....	732	738	756	.....	820?	773	751	682	676	664
1105	.56	.54	.75	.....	.07	.02	.09	.....	741	747	759	768?	778	730	710	688	683	670
1106	.42	.44	.55	.....	.13	.01	.15	.....	737	742	759	.....	828	755	731	690	683	671
1107	.37	.73	.50	.....	.02	.03	.20	.....	745	753	766	797?	843	798	775	696	690	680
1109	.47	.85	.78	.....	.15	.02	.11	.....	748	753	768	788	808	749	718	692	686	668
1111	.46	.27	.59	3.15	.03	.01	.03	.....	697	703	.....	.....	739	659	636	615	605	577
1112	.46	1.10	.66	2.95	.09	.03	.08	.....	720	725	.....	.....	758	646	.....	.....	613	588
1113	.55	1.15	.76	3.55	.03	.03	.....	.....	711	716	.....	.....	738	658	.....	.....	613	578
1114	.49	.52	.65	3.25	.02	.03	.....	.....	701	705	.....	.....	736	643	.....	.....	611	572
1133	.39	1.65	.75	3.30	.01	.02	.30	.....	719	733	746	.....	778	671	641	616	605	594
1135	.42	1.45	.83	3.25	.01	.....	.....	Mo 0.78	.....	720	751	.....	.....	.....	.....	477	426	.....
1255	.38	1.00	.75	2.90	.....	.....	.....	B .30	719	725	741	776	782	658	640	620	617	588
1262	.16	1.30	.64	2.80	.....	.....	.....	B .49	.....	739	745	795	817	701	685	622	613	590
1272	.40	.27	.69	.....	.....	.....	.....	Ce .35	732	737	.....	777	793	738	722	699	684	668
1274	.45	.33	.69	.....	.03	.....	.....	B .06	734	738	760	778	785	734	714	694	690	675
1279	.58	.23	.90	2.45	.01	.....	.....	Cu .62	682	697	.....	714	725	628	616	611	603	547
COMPARISON STEELS[a]																		
C 24	0.40	0.22	0.75	.....	.....	.....	.....	.....	726	732	748	783	802	743	729	681	672	654
A 51	.40	.28	.63	2.90	.....	.....	.....	.....	686	701	714	726	743	670	644	617	606	572

[a] These values are taken from Bureau of Standards Scientific Papers, No. 376.

By comparing C 24, 1104, and 1102, containing, respectively, 0.22, 0.66, and 1.15 per cent silicon, it will be noticed that silicon progressively raises the Ac ranges and the Ar_{3-2} range. The Ar_1 point is also raised, but not to so great an extent as the other values. This effect is also the same in the presence of nickel, as shown by Nos. 1111 and 1112.

Zirconium has about the same effect on the critical ranges as silicon, as will be observed from an inspection of the several data.

The effect of cerium is apparently rather small and irregular, as will be seen from Nos. C24 and 1272. The Ac_1 and Ar_1 points are raised somewhat and the Ac_{2-3} and Ar_{3-2} points decreased by about a similar amount.

Copper evidently produces the same result upon the critical ranges as an equal amount of nickel, No. 1279 having values that would be expected for a 3 per cent nickel steel with 0.58 per cent carbon.

In specimen No. 1135, containing 0.78 per cent of molybdenum, the Ac_1 range is about normal for a steel of similar composition but without the molybdenum, whereas the Ar_1 range has been considerably depressed, as has also been observed by other investigators.

From Nos. 1255, 1262, and 1264, containing boron in amounts from 0.06 to 0.49 per cent, and by comparison with Nos. C 24 and 1133, keeping in mind the variations in composition, it appears that boron raises all of the ranges somewhat.

2. MICROSTRUCTURE

(By S. Epstein)

It must be assumed that if zirconium or any of the other elements that were used are to have any virtue as additions to light armor-plate steels they should exert some noticeable effect on the microstructure of these steels at least in some stage of the heat-treated state, if not in the annealed condition. Also, if any true comparisons are to be drawn between steels of different chemical compositions from tests of their mechanical properties, it is plainly essential to know that the tested specimens have all been treated alike, or, if there are differences in the treatments, to know where they occur. It was the object, therefore, in the microscopic examination first to determine the rôle played by the zirconium, as well as the other addition elements in the steels, and, second, to examine the plates and test specimens for variations in soundness and heat treatment.

(a) ZIRCONIUM, TITANIUM, ALUMINUM

A steel containing zirconium can at once be recognized under the microscope by the presence of bright-yellow square inclusions not plainly visible at magnifications lower than 500 diameters (see Fig. 4). They are not affected by the ordinary alcoholic nitric or picric acid etching solutions, but retain their lustrous yellow color. In the steels examined these yellow inclusions were generally associated with orange-pink square inclusions and irregularly shaped purplish-gray ones. By a comparison of the chemical compositions of the steels the orange-pink ones were traced to the presence of titanium, while the purlpish-gray ones are probably due to alumium. However, this last point could not be established as positively as with the yellow and orange-pink inclusions (see Fig. 5). All of the inclusions manifested a tendency to form groups of tiny segregates, which when rolled, flattened out to thin plate-like streaks (see Fig. 6). These plates could readily be seen with the naked eye in the polished and etched specimens as yellow streaks. They could be noticed, also, in the fractures of some of the tested tension bars and impact specimens as laminations. In the specimens containing zirconium and titanium in which cracks were found the inclusions were most numerous very close to the cracks. Very few of the inclusions were found outside the segregates and streaks or away from the cracks.

Except for the bright-yellow square inclusions, which persisted throughout the working of the steel, the presence of zirconium was not found to affect the microstructure of the steels in any respect. Although the steels examined were regarded for the most part as alloy steels, the majority of the series under the microscope looked like plain carbon steels (see Fig. 7). In the air-cooled specimens it was considered that if any martensite or troostite were found it must be attributed to a self-hardening property or retardation of the Ar_1 transformation produced by the alloying elements. Otherwise, the structure would consist of granular pearlite and sorbite. Many of the other steels, to be referred to later (see Fig. 8), did show some martensite and troostite in the normalized specimens; but in no case was the presence of martensite or troostite in air-cooled specimens found to be due to zirconium. It may be that not all of the zirconium goes to form the characteristic yellow squares and that some of it goes into solution in the steel; but in that case it does not have a marked effect on the microstructure. In this

respect it may be likened to silicon, which goes into solution but the presence of which in small amounts can not be detected under the microscope. Thermal analyses seem to indicate that part at least goes into solution. Titanium and aluminum also formed characteristic inclusions, but otherwise gave no sign of their presence under the microscope.

The yellow square inclusions are very hard, but because they make up such a small proportion of the mass of the steel it can scarcely be conceived that they can exert a very great influence on its mechanical properties. The fact that they are associated in the form of segregates is a disadvantage, especially in an armor-plate steel. Wherever cracks were found in steels containing zirconium the yellow inclusions were most numerous near the cracks, and the conclusion that the cracks are in some way associated with the plates of inclusions appears to be warranted. The yellow inclusions of zirconium are very similar to the orange-pink ones of titanium, and with regard to the tendency of the former to segregate and form its negative effect on the microstructure it may also be compared to titanium, which is regarded as a scavenger and not a true alloying element. In general, zirconium, titanium, and aluminum may all be put in one class. They appear to act primarily as scavengers, and when they are not removed as part of the slag are present in the steel in the form of inclusions. They may go into solution in the steel, but in that case their presence can not be detected in the microscope and their effect would appear to be slight or negligible. In the form of inclusions they can not do much good, and if these are segregated and rolled out into thin plate-like streaks they may be detrimental.

(b) OTHER ALLOYING ELEMENTS

In contrast to zirconium, titanium, and aluminum, the other additions to the steels may be regarded as true alloying elements. Carbon, silicon, manganese, and nickel were not considered as special additions in this respect, and while their presence in the course of the examination was always noted they were not under particular observation. The other alloying elements may be grouped as follows: (1) Chromium, tungsten, vanadium, molybdenum; (2) cerium, uranium; (3) copper; (4) boron.

The first four—chromium, tungsten, vanadium, and molybdenum—go into solution and produce a martensitic pattern in the air-cooled specimens (see Fig. 8, *a*, *b*, *c*, *d*). Cerium and uranium go into solution and produce a martensitic pattern in the

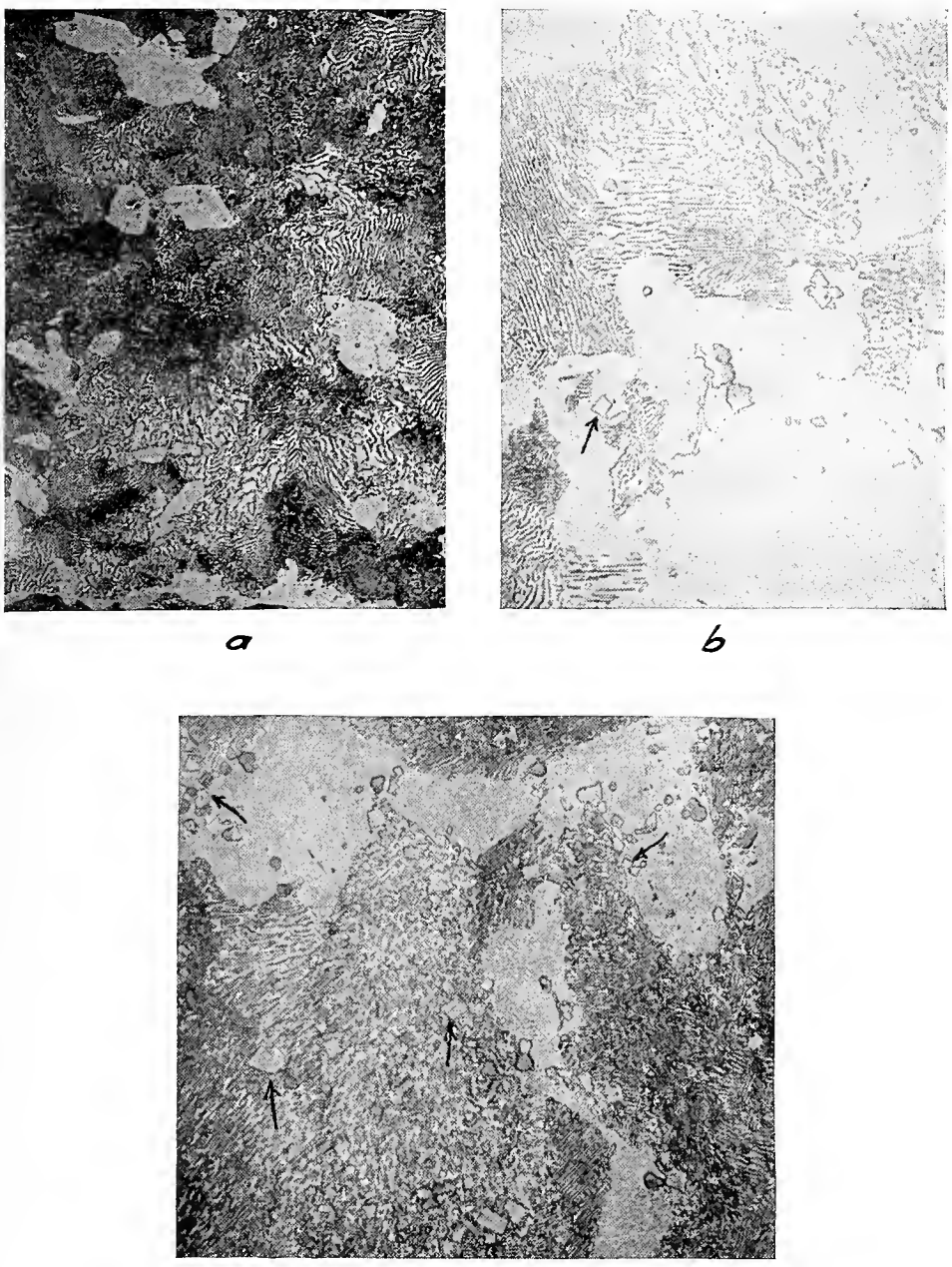


FIG. 4.—*Inclusions in ingot 1109 as cast containing 0.11 per cent zirconium. Etching, 2 per cent nitric acid*

(*a*) The bright yellow inclusions can not be distinguished at this magnification. ×100
(*b*) This spot shows the average number of inclusions which are indicated by the arrows. They are bright yellow in color. ×500
(*c*) A segregate of the bright yellow square inclusions is here shown. Most of these inclusions are segregated in this way. ×500

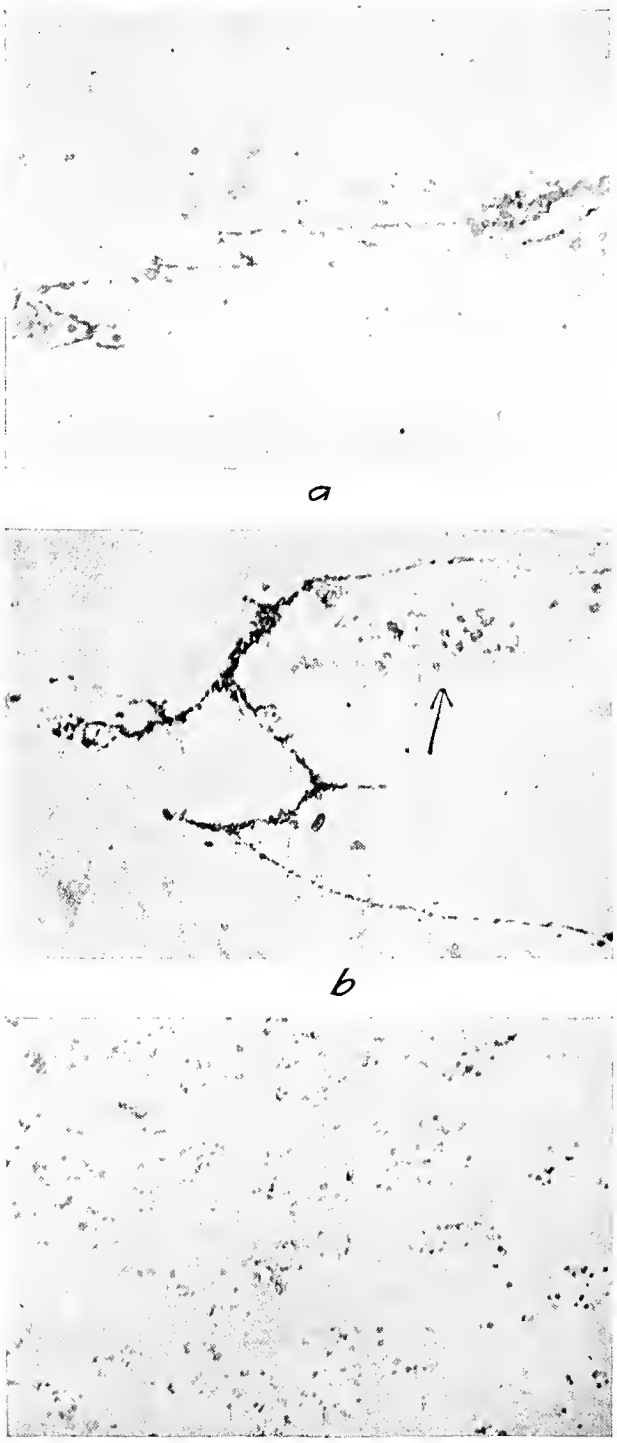


FIG. 5.—*Different types of inclusions found in the steels. Not etched. Magnification* $\times 500$

(*a*) Steel 1158. Al, 0.173 per cent; Ti, 0.028 per cent; Zr, 0.22 per cent. Of the square inclusions some are bright yellow and some are orange-pink. The yellow inclusions are due to zirconium, the orange-pink to titanium. The circular inclusions arranged in a threadlike continuity are purplish gray in color and may be due to aluminum

(*b*) Steel 1176. Al, 0.25 per cent; Ti, 0.09 per cent; Zr, 0.11 per cent. A threadlike streak of the gray similar to (*a*) is to be seen. In the cluster of square inclusions indicated by the arrow the larger light-colored ones are bright yellow, the smaller darker ones are orange-pink

(*c*) Steel 1213. Ti, 0.04 per cent; Zr, 0.34 per cent. This shows a segregate of small yellow and orange-pink inclusions. Most of these inclusions are found in these segregates, very few outside

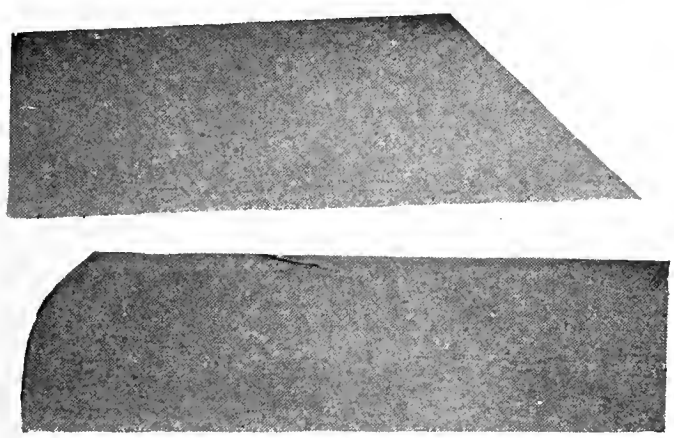
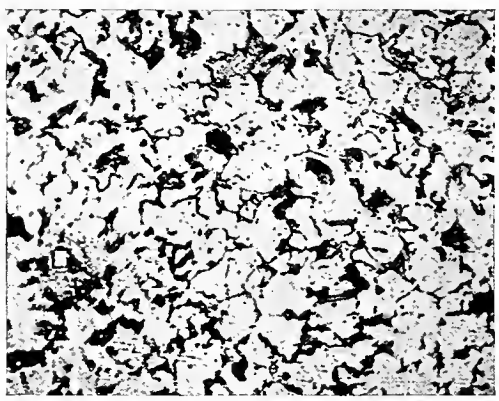


FIG. 6.—*Segregates of Ti and Zr inclusions rolled out into tin plate-like streaks*

Steel 1211. Butt—Ti, 0.07 per cent; Zr, 0.77 per cent. Top—Ti, 0.06 per cent; Zr, 0.92 per cent. The thin plates appear as yellow streaks easily visible to the naked eye in the polished and etched specimens. In the fractures of the impact and tension bars they look like laminations. Not etched. X2

a



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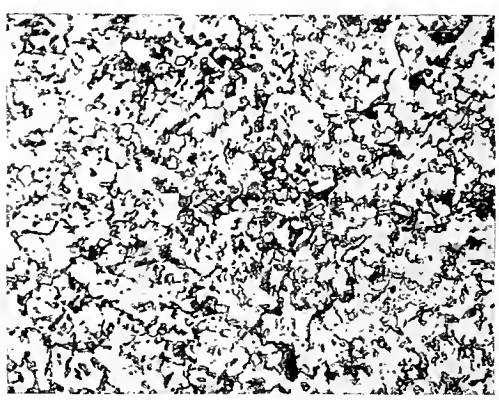


c

FIG. 7.—*Microstructure of air-cooled specimens of steel containing Ti and Zr. Etching, 2 per cent nitric acid; magnification, ×500*

(*a*) Steel 1185. C, 0.26 per cent; Ni, —; Al, 0.021 per cent; Zr, 0.30 per cent. The structure is granular pearlite and ferrite

(*b*) Steel 1186. C, 0.26 per cent; Ni, 2 per cent; Al, 0.013 per cent; Ti, 0.04 per cent; Zr, 0.24 per cent. The structure is again granular pearlite and ferrite. The structure is not essentially different from that of a steel containing a similar percentage of nickel but no other additions

(*c*) Steel 1225. C, 0.27 per cent; Ni, 3.04 per cent; Ti, 0.22 per cent; Zr, .034 per cent. The structure is granular pearlite and ferrite. In no case was the presence of Ti or Zr found to produce a martensitic pattern

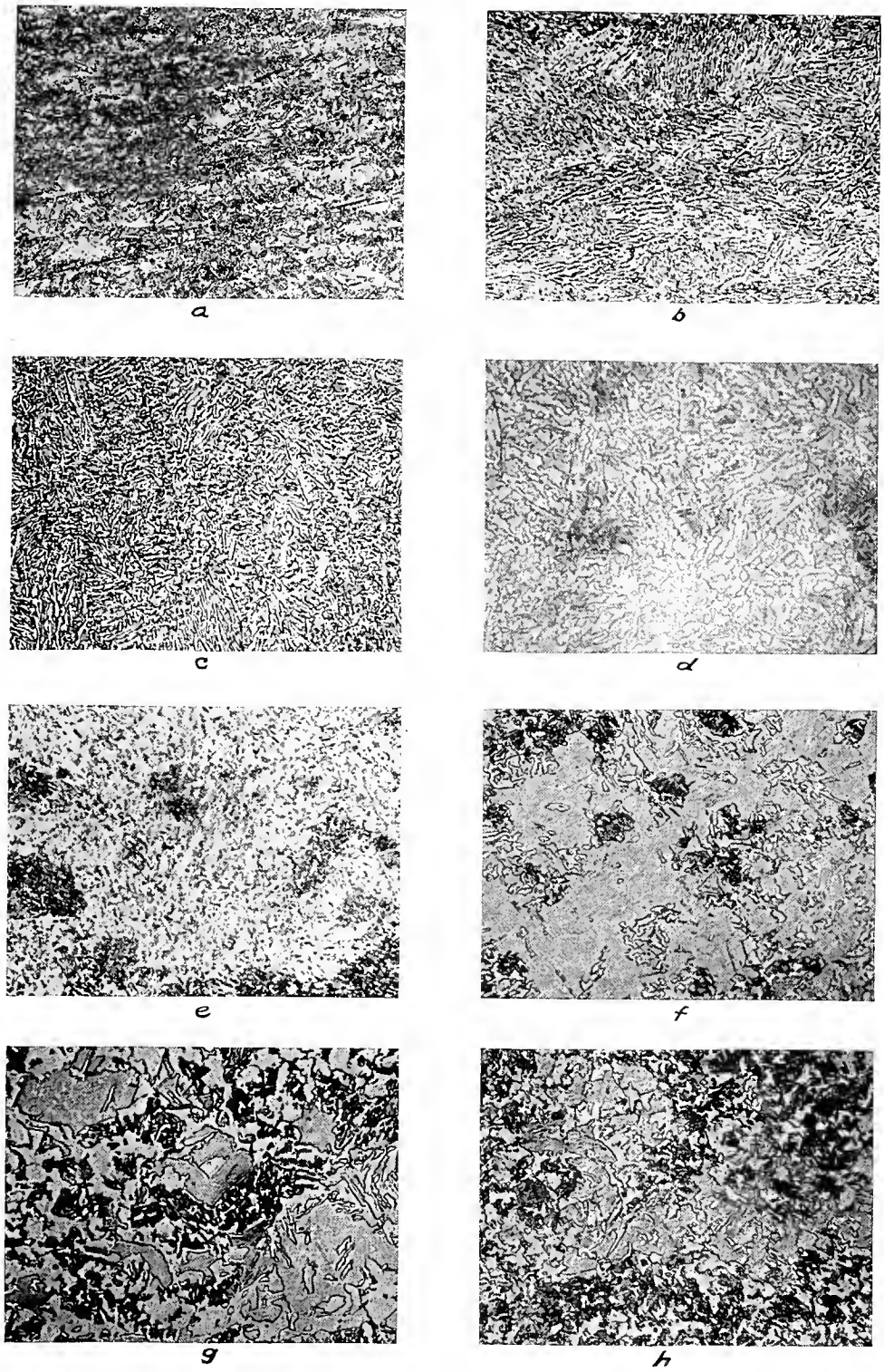
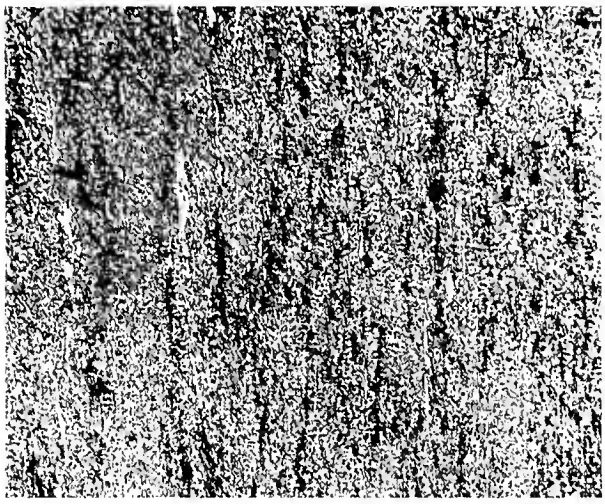


FIG. 8.—*Microstructure of air-cooled specimens containing other alloying elements. Etching, 2 per cent nitric acid; magnification,* $\times 500$

(*a*) Steel 1155. C, 0.38 per cent; Ni, 3.60 per cent; Cr, 1.14 per cent. The angular structure is typical of air-cooled nickel chromium steels
(*b*) Steel 1178. C, 0.32 per cent; Ni, 3.5 per cent; Cr, 2 per cent; W, 0.90 per cent. The angular structure is characteristic
(*c*) Steel 1207. C, 0.60 per cent; Ni, 3.6 per cent; Vd, 32 per cent
(*d*) Steel 1135. C, 0.41 per cent; Ni, 3.5 per cent; Mo, 0.78 per cent
(*e*) Steel 1258. C, 0.39 per cent; Ni, 2.65 per cent; Ce, 1.35 per cent. This steel displays a characteristic martensitic structure, due doubtless to the presence of the cerium
(*f*) Steel 1228. C, 0.63 per cent; Ni, 3.01 per cent; N, 0.52 per cent. The uranium has produced a martensitic pattern
(*g*) Steel 1226. C, 0.40 per cent; Si 1.61 per cent; M, 0.90 per cent; Ni, 3.04 per cent. The combination of high Si, Mn, and Ni has resulted in a martensitic pattern
(*h*) Steel 1282. C, 0.45 per cent; Si, 1.10 per cent; Mn, 0.84 per cent; Ni, 1.92 per cent; Cu, 1.35 per cent. The high percentage of copper had produced some martensite



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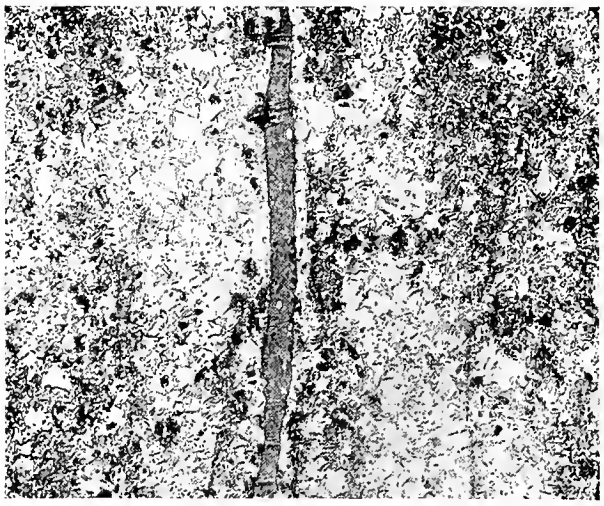
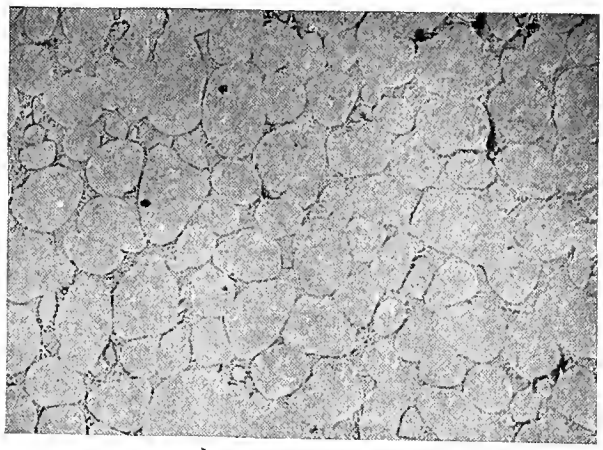


b

FIG. 9.—*Inclusions in cerium and uranium steels. Etching, 2 per cent nitric acid*

(*a*) Steel 1252. Air-cooled, Ce, 0.55 per cent. A large number of inclusions were segregated in streaks in this specimen. These streaks could be plainly seen with the naked eye. The shape and color of the inclusions can not be distinguished at the magnification of this micrograph, but at 500 diameters most of them appear as circular gray inclusions, while some are orange with gray markings inside the circumferences. The latter inclusions were found only in the cerium steels. ×50

(*b*) Steel 1228. Air-cooled uranium, 0.52 per cent. A large number of inclusions were segregated in this spot, together with the long slag inclusion shown here. At higher magnification it can be seen that the inclusions are circular and of a deep blue color. The typical angular structure resulting from the presence of uranium is especially noticeable in this segregated area. ×100



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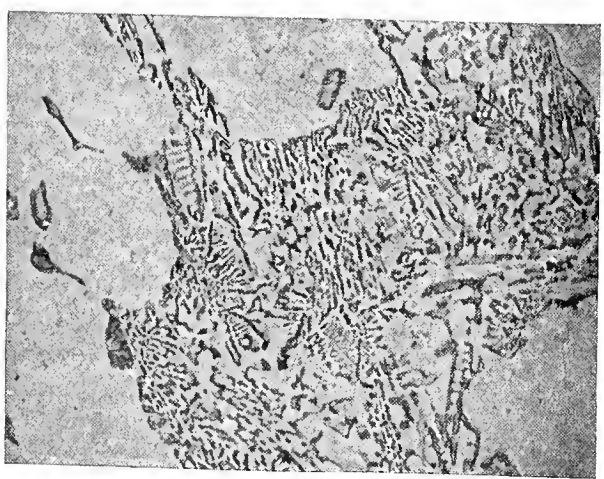

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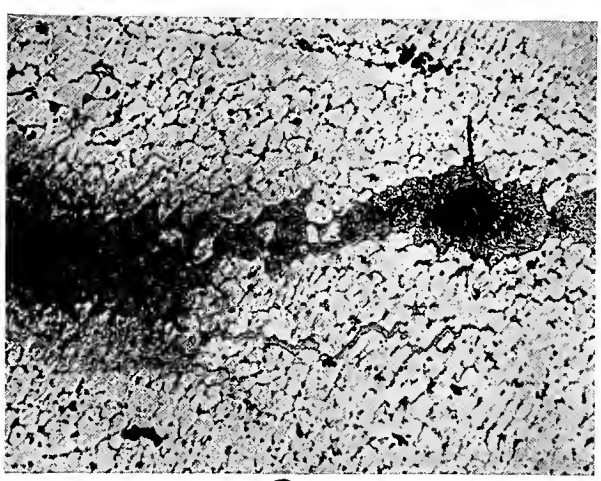


c

FIG. 10.—*Characteristic structure of boron steel*

(*a*) Steel 1262, containing 0.49 per cent B, which broke in the rolls. This shows the eutectic network. Not etched. ×100

(*b*) The eutectic etches dark with sodium picrate. This also shows where some of the eutectic has coalesced into the circular particles. Etching, sodium picrate, ×500

(*c*) The eutectic is fusible at the temperature ordinarily used in rolling. The cracks in the broken ingot all followed the network of the eutectic. This micrograph shows where a larger mass of eutectic has located a crack. Etching, sodium picrate, ×50

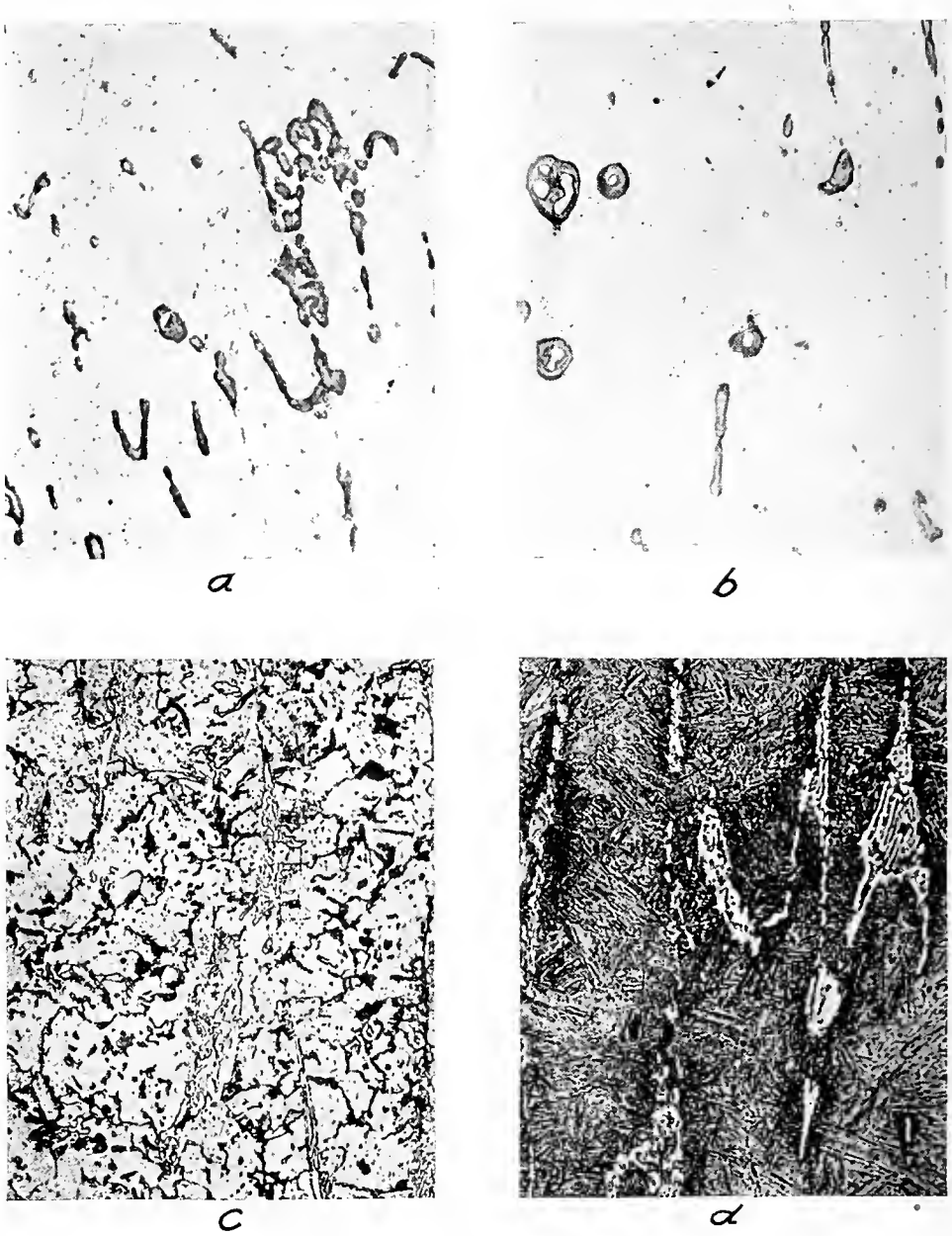
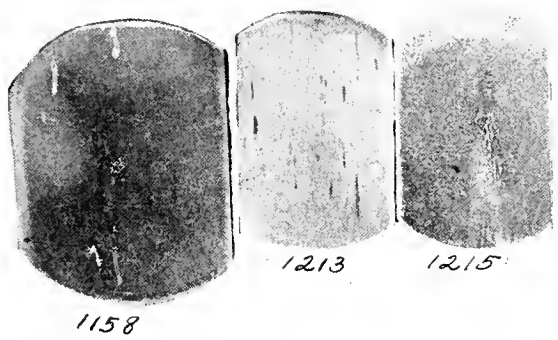


FIG. 11.—*Rolled and heat-treated steels containing boron, ×500*

(*a*) Steel 1275. B, 0.08 per cent. This shows particles of the boron compound in the rolled and normalized specimen. Etching, sodium picrate
(*b*) Same steel as (*a*). This shows the particles of the boron compound in the quenched specimen. Etching, sodium picrate
(*c*) Steel 1263. B, 0.30 per cent. This is the air-cooled specimen. The white sharply outlined particles are the boron compound. Etching, 2 per cent nitric acid
(*d*) Same steel as (*c*), quenched. There are no definite circular and elongated particles, but a eutectic structure is present. This may be due to the fact that the specimen was quenched from a temperature high enough to allow the eutectic to form again. Etching, 2 per cent nitric acid



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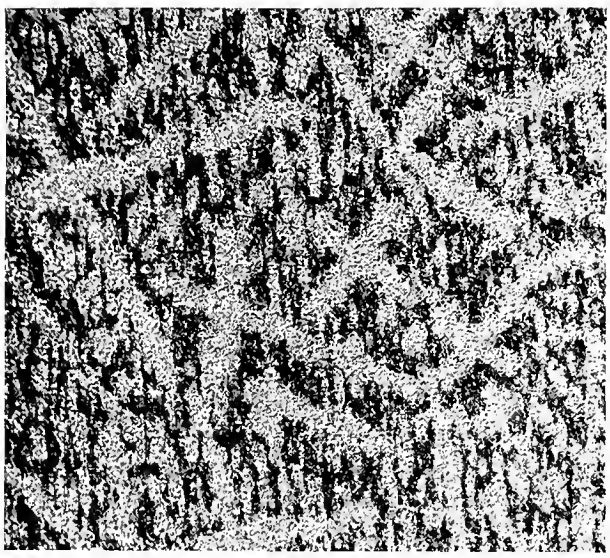
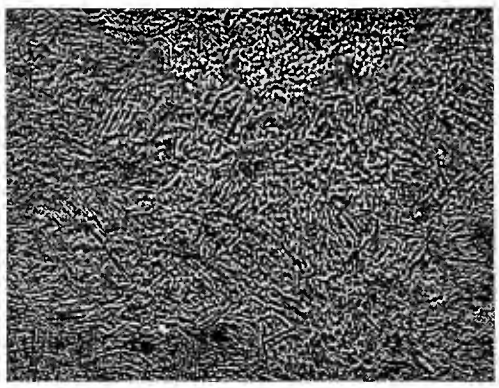


b

FIG. 12.—*Types of flaws existing in some of the steels. Etching, 2 per cent nitric acid*

(*a*) Steel 1158, H. T., cracked. Steel 1213, H. T., yellow streaks of titanium and zirconium inclusions. Steel 1215, H. T., dendritic. These specimens were taken from the shoulders of the tension bars. In the other steels that showed cracks the cracks were about the same size as in 1158, but there were not as many, generally one or two. ×1

(*b*) This shows the dendrites in Steel 1215, H. T., at higher magnification. ×50



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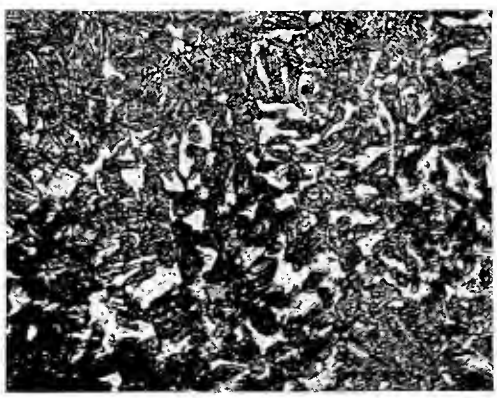

b

FIG. 13.—*Influence of considerable amounts of ferrite on tensile properties of heat-treated specimens*, ×50

(*a*) Steel 1144. C, 0.38 per cent; Si, 1.35 per cent; Mn, 0.84 per cent; Ni, 3.10 per cent; Al, 0.005 per cent; Ti, 0.017 per cent; Zr, 0.32 per cent. This steel gave 307 000 lb./in.^{2} tensile strength with 7.5 per cent elongation in 2 inches, and 21.7 per cent, reduction in area in the heat-treated bar. The structure is fine martensite

(*b*) Steel 1197. C, 0.32 per cent; Si, 1.37 per cent; Mn, 0.60 per cent; Ni, 3.05 per cent; Al, 0.02 per cent; Ti, 0.17 per cent; Zr, 0.32 per cent. This steel is of almost identical chemical composition as one shown in (*a*), but gave only 217 000 lb./in.^{2} tensile strength with 3 per cent elongation in 2 inches and 27.5 per cent reduction in area. The carbon is slightly lower and may partly account for the large amount of ferrite shown in the micrograph, but it is more probable that this is, because the specimen was not heated high enough before quenching

air-cooled specimens (see Fig. 8, *e*, *f*), but the steels also show characteristic inclusions. At a magnification of 500 diameters the two cerium steels that were examined were found to contain a large number of gray inclusions, and also some large circular orange inclusions, with interior light-gray markings. The uranium steels contained deep-blue inclusions (see Fig. 9). It seems that cerium and uranium, in a way somewhat similar to manganese (see Fig. 8, *g*), act both as true alloying elements and to produce soundness in the metal. Copper goes into solution, but did not produce a martensitic pattern in the air-cooled specimens, except in the one of high copper content, 1.35 per cent (see Fig. 8, *h*).

Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron (see Fig. 10). The difficulty experienced in rolling the ingots containing boron is due to the fusibility of this eutectic at the temperatures ordinarily used for rolling. In the ingots that broke in the rolls the cracks in the polished specimens were found to follow the eutectic structure observed in the steels as cast, but in other places no traces were visible. Instead hard spherical particles, evidently of a single constituent of the same appearance as iron carbide, were found (see Fig. 11, *a*, *b*). The mechanical working probably breaks up the eutectic, the iron of the eutectic is absorbed by the iron of the matrix, while the iron-boron-carbon compound coalesces into the hard circular particles. These particles no longer form a weak brittle network and may have an appreciable hardening effect on the properties of the steel which may be desirable for the purpose of armor plate. Care must be taken, however, in the final heat treatment that the steel is not heated to too high a temperature before quenching, as the eutectic will then again appear and render the steel unsuitable (see Fig. 11, *d*). In the unetched state both the eutectic and the hard circular particles are pink, they both etch dark with sodium picrate, similar to simple iron carbide, and are not etched by 2 per cent nitric-acid etching, but appear white in contrast to the etched matrix (compare Fig. 11, *a*, *b* with Fig. 11, *c*).

All of the above elements are true alloying additions; they are metallic constituents of the finished steel. The properties they confer upon the steel can not be established from a microscopic examination alone, but must be determined by physical tests. In the light of the considerations indicated above, however, they may all give good results, but more care perhaps must be taken

in the making and treatment of the cerium, uranium, and boron steels than of the others.

(c) SOUNDNESS OF THE STEELS AND STRUCTURES OF THE NORMALIZED AND HEAT-TREATED SPECIMENS

Not all the steels that were made up were examined under the microscope. Typical specimens, however, were chosen from every class of chemical composition, and all those specimens that gave exceptional or unexpected values in the tension tests were examined. Some samples were examined from the ingot as cast and some from the plates as rolled, but the great majority of the specimens were taken from the tested tension bars.

In most of the steels that contained zirconium and titanium in appreciable amounts there were found in the polished and etched specimens the thin, yellow streaks which are the segregates of the zirconium and titanium inclusions rolled out into plates (see Fig. 12, *a*, steel 1213). Many of the steels also showed small longitudinal cracks in the specimens (see Fig. 12, *a*, steel 1158), while in others there appeared a pronounced dendritic pattern (see Fig. 12, *a*, steel 1215, and Fig. 12, *b*). These features are of sufficient size as to be seen with the naked eye. The streaks and cracks, since they occur longitudinally in the specimens, should not be expected to have much effect in lowering the tensile properties as measured. The dendritic pattern, which of itself is considered undesirable, was not found to be associated particularly with steels that gave low values in tension. In fact, some of the steels which had the highest tensile properties showed a dendritic pattern. This is perhaps because these steels were rolled with the least number of reheatings, giving a better plate by avoiding repeated heatings and oxidation. The steels that were rolled in the latter part of the investigation, presumably most expertly, gave the largest percentage of dendritic structures.

The following is a list of these steels which showed small cracks in the specimens examined (see Fig. 12) and those which had a dendritic structure. The normalized steels are marked N. and the heat-treated ones H. T.:

Cracked:	Dendritic:
1106, N.	1103, N. and H. T.
1107, N.	1132, N. and H. T.
1109, N.	1135, N.
1119, N.	1136, N.
1157, H. T.	1167, N.
1158, N. and H. T.	1168, N. and H. T.

Cracked—Continued
1176, H. T.
1178, N.
1189, H. T
1211, H. T.
1213, N.
1228, N. and H. T.
1229, H. T.
1236, N. and H. T.
1237, H. T.
1258, N. and H. T.
1274, N. and H. T.
1275, N.
1278, N. and H. T.
1286, N.

Dendritic—Continued
1190, N.
1200, N.
1205, N.
1206, N.
1207, N. and H. T.
1215, N. and H. T.
1216, N.
1219, N. and H. T.
1224, N.
1227, N. and H. T.
1231, N.
1237, N.
1244, N. and H. T.
1252, N.—Streaky.
1285, N.
1286, N. and H. T.

The normalized, as well as the heat-treated specimens, were partially decarburized uniformly to the depth of 0.005 inch along the gage length of the tension specimen, which makes 0.010 inch of the diameter of the gage length decarburized. The differences in the microstructures of the air-cooled specimens have already been described. In the heat-treated specimens those that gave the best results in the tension tests invariably had a structure of fine martensite. Wherever appreciable amounts of ferrite were found, together with the martensite in the quenched and tempered specimens, the tension values were not so good. In many cases unexpected low results could be traced to the presence of relatively large amounts of ferrite (see Fig. 13). The variations in the drawing temperatures, if there were any, could not be detected in the microstructure.

Altogether, in this part of the examination 160 micrographs of the steels in the cast, rolled, and finally heat-treated conditions were taken. For lack of space they can not be given here, but they were invaluable in helping to interpret the results of the mechanical tests. By means of this survey of the microstructures of the samples those containing flaws were discovered and eliminated, and any irregular results could be explained. The microscopic "check-up" thus served to relieve any doubts concerning single samples and helped to give weight to the general conclusions of the investigation.

3. MECHANICAL PROPERTIES

(a) TENSILE TESTS

Since the rolled material was one-half inch or less in thickness, it was impossible to use the standard form of tensile specimen having a diameter in the reduced section of 0.505 inch. A shoulder type specimen was used, having a diameter of 0.300 inch at the reduced section and a gage length of 2 inches, as shown in Fig. 14. This ratio of gage length to area of specimen gives values of elongation somewhat less than would be obtained with standard size specimens, and this fact should be borne in mind in interpreting the results. The tensile and also the impact specimens

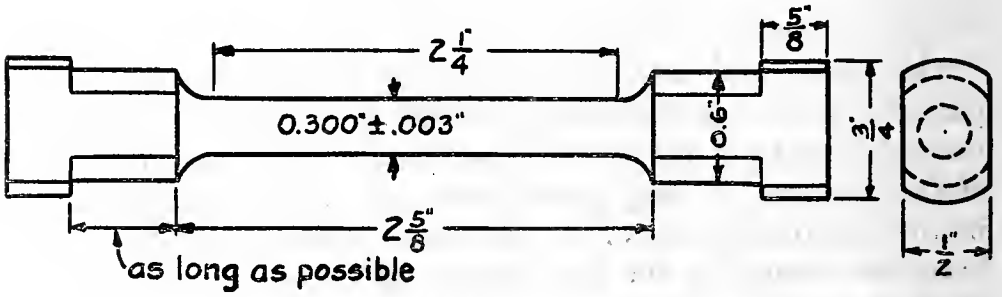

FIG. 14.—*Dimensions of tensile specimens*

were completely machined before heat treatment and not ground before testing.

Tensile tests were made on either a 50 000-pound or 100 000-pound Riehle testing machine. Proportional limit was determined from plotted stress strain curves, strain being measured by means of a Berry strain gage. In a few cases the specimens were too short to admit of fastening a strain gage to the specimen, and blanks appear in the tables (Tables 11–22) for these cases. Yield point was determined by the "drop-of-the-beam" method where any "drop" was observed. Reduction of area and elongation were obtained by the usual measurements after fracture.

Tables 11–22 give the results of the tensile tests on all the steels. It will be noted here that several of the steels have a tensile strength of well above 300 000 lbs./in.^{2}, accompanied by appreciable ductility. No. 1207, with a tensile strength of 344 000 lbs./in.^{2}, was the highest value observed.

TABLE 5.—Hardness Measurements on Plate

[*Indicates specimen not completely broken]

Ingot No.	Thickness	Hardness numerals				Ingot No.	Thickness	Hardness numerals			
		Brinell		Scleroscope				Brinell		Scleroscope	
	Inch						Inch				
1101	3/8	334	293	30	26	1159	3/8	294	327	32	32
	1/2	405	444	52	47		1/2	603	477	55	45
1102	3/8	240	245	27	25	1160	3/8	573	279	.....	
	1/2	217	223	21	22		1/2	556	545	60	52
1103	3/8	207	207	23	23	1161	3/8	285	440	24	42
	1/2	223	212	32	31		1/2	432	512	31	47
1104	3/8	207	194	20	21	1162	3/8	321	337	24	23
	1/2	187	205	20	22		1/2	387	338	38	37
1105	3/8	172	241	28	28	1163	.....	219	234	21	22
	1/2	232	207	30	28						
						1164	.....	375	340	30	28
1106	3/8	189	235	24	25	1165*	.....	338	346	36	40
	1/2	202	216	21	26	1166	.....	430	514	.....	
1107	3/8	189	182	22	20	1167	.....	364	387	33	32
	1/2	187	196	20	21	1168	.....	421	385	44	43
1109	3/8	236	231	24	..						
	1/2	244	255	26	..						
1111	3/8	317	335	30	..	1169	.....	640	571	.....	
	1/2	340	351	33	..	1170	.....	550	600	61	57
1112	3/8	415	302	41	31	1171	.....	387	447	34	41
	1/2	290	438	39	40	1172	.....	424	428	43	37
						1173	.....	328	302	28	26
1113	3/8	467	244	39	34						
	1/2	477	484	43	43	1174	.....	226	206	19	19
1114	3/8	537	491	48	49	1175*	.....	472	467	52	52
	1/2	555	520	62	60	1176	.....	470	481	36	38
1115	3/8	364	354	34	37	1177*	.....	477	477	55	55
	1/2	361	340	47	42	1180	.....	196	211	19	23
1117	3/8	626	508	43	43						
	1/2	600	576	57	68	1181	.....	208	216	20	21
1118	3/8	626	626	54	54	1182	.....	213	224	20	21
	1/2	.....	.....			1183	.....	257	241	.....	
						1184	.....	171	172	18	19
1119	3/8	387	364	42	40	1185	.....	211	244	.....	
	1/2	555	600	54	52						
1120	3/8	495	470	52	43	1186	.....	381	403	.....	
	1/2	418	495	47	52	1187	.....	300	311	.....	
1128	3/8	380	370	35	36	1188	.....	342	336	.....	
	1/2	467	418	42	45	1189*	.....	351	360	42	44
1129	3/8	444	387	39	42	1190	.....	351	325	34	29
	1/2	475	460	47	42						
1130	3/8	387	370	37	35	1191	.....	344	338	29	28
	1/2	338	375	37	35	1192	.....	228	217	24	23
						1193	.....	252	233	26	26
1131	3/8	652	635	.....		1194	.....	439	457	52	53
	1/2	575	534	53	63	1195	.....	444	403	42	38
1132	3/8	558	552	.....							
	1/2	589	626	55	65	1196	.....	465	398	46	34
1133	3/8	387	488	40	54	1197	.....	415	369	36	36
	1/2	444	402	45	40	1198	.....	209	218	23	24
1134	3/8	477	470	42	48	1199	.....	216	210	24	23
	1/2	444	477	55	58	1200	.....	321	302	37	28
1135	3/8	444	336	.....							
	1/2	512	444	47	43	1201	.....	268	266	26	26
						1202	.....	207	199	21	21
1136	3/8	491	479	.....		1204*	.....	477	457	50	53
	1/2	410	375	37	34	1205	.....	505	512	41	45
1138	3/8	589	608	.....		1206	.....	481	491	42	47
	1/2	578	591	50	56						
1144	3/8	578	346	53	26	1207	.....	627	600	55	55
	1/2	589	555	55	50	1208	.....	629	616	69	61
1145	3/8	351	245	35	25	1209	.....	600	555	66	62
	1/2	444	352	41	31	1210	.....	378	411	38	44
1146	3/8	418	390	32	32	1211	.....	456	447	46	40
	1/2	478	321	45	28						
						1212*	.....	367	361	43	45
1147	3/8	487	450	52	60	1213	.....	471	564	42	51
	1/2	387	477	37	45	1214	.....	481	495	41	37
1155	3/8	585	555	.....		1215	.....	600	553	53	48
	1/2	519	550	51	53	1216	.....	418	387	34	35
1156	3/8	477	516	43	45						
	1/2	537	534	56	55	1217	.....	475	477	55	55
1157	3/8	418	423	38	39	1218	.....	310	278	30	28
	1/2	518	522	55	59	1219	.....	235	228	23	23
1158	3/8	544	640	.....		1220	.....	441	337	45	36
	1/2	452	452	50	51	1221	.....	312	323	33	33

TABLE 5.—Hardness Measurements on Plate—Continued

[*Indicates specimen not completely broken]

Ingot No.	Thickness	Hardness numerals		Ingot No.	Thickness	Hardness numerals	
		Brinell	Sclero-scope			Brinell	Sclero-scope
	Inch				Inch		
1222*		366 367	47 49	1259		596 605	47 48
1223		357 317	33 26	1260		532 569	57 48
1224		406 438	32 34	1261		207 223	18 19
1225		467 387	32 41	1263		402 373	37 40
1226		430 454	36 37	1264		387 396	43 43
1227		550 537	54 54	1267*		180 183	27 25
1228		629 627	66 62	1268		252 219	23 22
1229		585 573	57 55	1269*		207 188	
1230		603 605	70 69	1270*		351 364	20 21
1231		520 474	47 42	1271*		341 342	38 40
1232		494 505	44 46	1272*		250 321	25 30
1233		321 311	28 26	1273*		255 216	32 24
1234		364 375	30 30	1274*		444 418	52 43
1235		351 241	23 22	1275*		555 600	55 60
1236		484 472	54 53	1276*		534 570	52 54
1237		600 585	56 54	1277*		410 444	42 51
1238		444 474	46 49	1278*		395 397	44 43
1239		532 555	59 61	1279*		490 520	50 60
1240		509 516	41 42	1280*		510 486	60 57
1241		520 512	47 47	1281*		508 468	60 59
1242		387 430	39 41	1282*		510 475	57 53
1243		460 438	42 43	1283*		539 512	57 58
1244		441 420	44 45	1285*		475 430	49 47
1245*		525 493	56 57	1286*		520 508	54 52
1246		444 444	39 36	1289*		340 447	38 49
1247		366 418	33 36	1290*		455 498	51 55
1248		248 256	20 20	1291*		464 478	50 49
1249		361 371	19 18	1292*		522 486	60 60
1250		324 324	28 26	1293*		418 470	39 47
1251		477 495	39 37				
1252		477 487	40 39				
1253		600 560	53 49				
1256		532 495	49 49				
1257		524 477	52 47				
1258		441 440	38 40				

(b) IMPACT TESTS

Impact tests were made on heat-treated specimens from all heats beyond No. 1155 and a few previous, the heat treatment being the same as for the tensile specimens and plates. Hardness tests made on a few impact specimens gave sufficient evidence that the impact specimens were in a structural condition similar to the tensile specimens. An Izod machine using a cantilever type of specimen was used in all impact tests.

Here, again, the thickness of the available material precluded the use of the standard type of specimen in all cases. For those plates which would not admit of making a round specimen 0.450-inch diameter (see Fig. 15), the largest diameter possible in multiples of 0.050 inch, was used and the notch made geometrically similar to the larger specimens. The total length of the specimens re-

mained constant, so as not to alter the striking distance. The specimens of small size were held in the anvil of the impact machine by means of hardened steel split sleeves having an outside diameter of 0.450 inch and an inside diameter to fit the specimen. This sleeve was inserted in the anvil flush with its top surface and the impact specimens properly aligned by means of a templet. The height of fall of the pendulum was varied proportionally to the size of the specimen, although theoretically this should not be necessary.

The area of the specimens at the notch was computed and the energy absorbed in breaking for unit area determined, a value which has been called the specific impact work. The results of the tests are given in Table 6. While the law of similarity has not been definitely shown to hold for impact specimens as for other

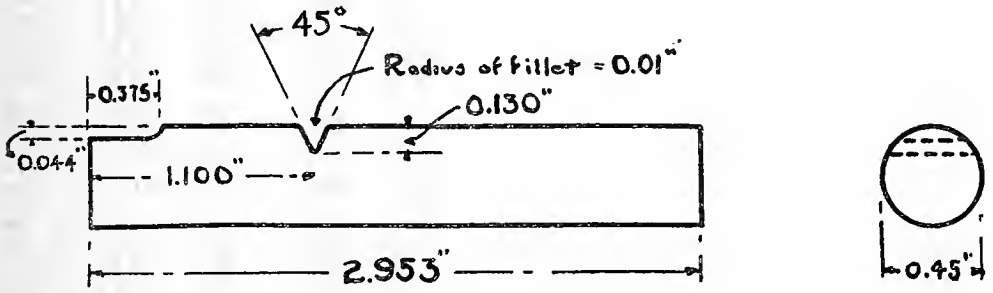

FIG. 15.—*Dimensions of impact specimens*

forms of mechanical testing, the method used was considered the most desirable that the circumstances would permit.

A high impact value does not always indicate a superior steel, since such values are many times accompanied by low tensile strength. Thus, all the steels which had an impact value greater than 200 foot-pounds per square inch also gave tensile strengths less than about 130 000 lbs./in.^{2}, except No. 1252, which had a tensile strength of 324 800 lbs./in.^{2}. On the other hand, if we select all those steels which showed an impact value less than 50 we note that the majority of that group have a tensile strength in excess of 275 000 lbs./in.^{2}, although a few fall even below 100 000 lbs./in.^{2}, the latter being clearly inferior steels. Those steels, then, that show fair values of impact, together with high tensile strength, should be considered the best steels, since they combine strength with toughness.

TABLE 6.—Impact Tests (Izod Machine)

[*Indicates specimen not completely broken]

Ingot No.	Diameter of specimen	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
1135	0.450	0.1210	120	7.0	58
1136	.450	.1210	120	8.0	66
1138	.447	.1196	120	6.5	54
1155	.447	.1196	120	13.5	113
1156	.447	.1196	120	5.0	42
1157	.450	.1210	120	13.5	112
1158	.448	.1201	120	5.5	46
1162	.445	.1187	120	6.0	51
1163	.448	.1201	120	29.5	246
1164	.347	.0732	75	8.0	109
1165	.449	.1206	120	9.5	79
1166	.346	.0730	75	8.0	110
1167	.350	.0736	75	4.5	61
1168	.450	.1210	120	12.0	99
1169	.347	.0732	75	5.5	75
1170	.351	.0738	75	4.5	61
1171	.454	.1229	120	16.5	134
1172	.354	.0742	75	11.0	148
1173	.353	.0741	75	9.0	121
1174	.449	.1206	120	16.0	133
1175	.447	.1196	120	10.5	88
1176	.354	.0742	75	8.0	108
1177					
1178	.450	.1210	120	9.5	78
1180	.450	.1210	120	14.0	116
1181	.296	.0524	60	6.5	124
1182	.445	.1187	120	15.0	126
1183	.349	.0735	75	6.0	82
1184	.444	.1182	120	28.0	237
1185	.446	.1192	120	42.0	357
1186	.441	.1168	120	19.0	163
1187	.349	.0735	75	9.0	122
1188	.348	.0733	75	10.0	136
1189	.350	.0736	75	8.0	109
1190	.450	.1210	120	14.5	120
1191	.354	.0742	75	7.5	101
1192	.450	.1210	120	24.5	202
1193	.354	.0742	75	17.5	236
1194	.447	.1196	120	10.5	88
1195	.349	.0735	75	7.5	102
1196	.347	.0732	75	9.5	130
1197	.348	.0733	75	8.5	116
1198	.449	.1206	120	75.5	*625
1199	.345	.0729	75	33.5	*460
1200	.447	.1196	120	14.5	121
1201	.349	.0735	75	16.0	218
1202	.452	.1220	120	41.5	340
1204	.449	.1206	120	12.0	100
1205	.350	.0736	75	7.0	95
1206	.349	.0735	75	9.5	129
1207	.350	.0736	75	5.5	75
1208	.446	.1192	120	4.5	38
1209	.350	.0736	75	1.5	20
1210	.446	.1192	120	14.0	117
1211	.348	.0733	75	9.5	130
1212	.447	.1196	120	12.0	100
1213	.447	.1196	120	4.5	38
1214	.349	.0735	75	6.5	88
1215	.447	.1196	120	6.0	50
1216	.448	.1201	120	13.5	112
1217	.350	.0736	75	6.5	88
1218	.349	.0735	75	9.0	122
1219	.448	.1201	120	17.5	146
1220	.447	.1196	120	9.0	75
1221	.353	.0741	75	9.0	121

TABLE 6.—Impact Tests (Izod Machine)—Continued

[*Indicates specimen not completely broken]

Ingot No.	Diameter of specimen	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
1222	0.450	0.1210	120	11.0	91
1223	.449	.1206	120	9.5	79
1224	.353	.0741	75	7.5	101
1225	.349	.0735	75	8.5	116
1226	.298	.0534	60	4.5	83
1227	.299	.0539	60	4.0	74
1228	.299	.0539	60	2.0	37
1229	.348	.0733	75	8.0	109
1230	.296	.0524	60	.5	10
1231	.350	.0736	75	8.0	109
1232	.299	.0539	60	4.0	74
1233	.300	.0544	60	4.0	74
1234	.349	.0735	75	6.5	88
1235	.350	.0736	75	13.5	183
1236	.349	.0735	75	8.5	116
1237	.351	.0738	75	4.5	61
1238	.298	.0534	60	4.5	84
1239	.299	.0539	60	1.0	19
1240	.299	.0539	60	6.5	120
1241	.298	.0534	60	1.5	28
1242	.351	.0738	75	6.5	88
1243	.300	.0544	60	7.5	138
1244	.349	.0735	75	7.5	102
1245	.299	.0539	60	3.5	65
1246	.300	.0544	60	2.5	46
1247	.350	.0736	75	4.0	54
1248	.351	.0738	75	6.0	81
1249	.349	.0735	75	10.0	136
1250	.299	.0539	60	5.5	102
1251	.299	.0539	60	2.0	37
1252	.298	.0534	60	13.5	252
1253	.298	.0534	60	2.5	47
1256	.450	.1210	120	21.5	174
1257	.400	.0833	100	6.0	72
1258	.350	.0736	75	5.0	68
1259	.399	.0827	100	8.0	97
1260	.400	.0833	100	6.0	72
1261	.449	.1206	120	5.8	48
1263	.400	.0833	100	4.0	48
1264	.450	.1210	120	5.5	46
1267	.398	.0821	100	3.0	37
1268	.400	.0833	100	6.0	72
1269	.449	.1206	120	14.5	120
1270	.398	.0821	100	10.5	128
1271	.449	.1206	120	10.5	91
1272	.397	.0815	100	10.5	128
1273	.397	.0815	100	31.0	380
1274	.389	.0827	100	3.0	36
1275	.450	.1210	120	5.0	41
1276	.450	.1210	120	4.2	35
1277	.348	.0733	75	8.0	109
1278	.450	.1210	120	19.5	161
1279	.448	.1201	120	4.0	34
1280	.448	.1201	120	6.0	50
1281	.449	.1206	120	4.0	33
1282	.450	.1210	120	7.0	58
1283	.449	.1206	120	3.0	25
1285	.449	.1206	120	10.0	83
1286	.449	.1206	120	8.0	66
1289	.349	.0735	75	7.0	95
1290	.350	.0736	75	6.0	82
1291	.349	.0735	75	5.5	75
1292	.350	.0736	75	5.5	75
1293	.349	.0735	75	7.0	95

(c) HARDNESS TESTS

Hardness tests were made on the tensile specimens and on the hardened plates. For the tensile specimens this consisted of two Brinell impressions on the ends of the broken specimens after grinding off the outside surface. Scleroscope hardness was also determined on the same material, several readings being taken with a recording scleroscope.

On the plates opposite corners were ground down and duplicate Brinell and several scleroscope determinations made at each posi-

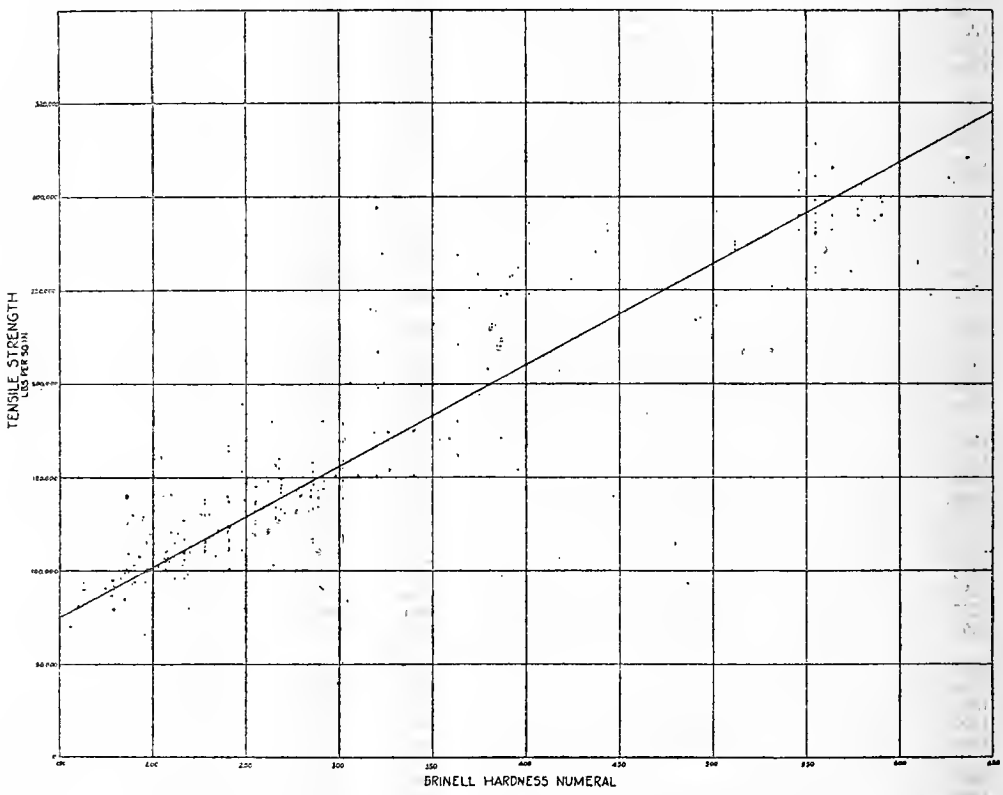

FIG. 16.—*Relation between tensile strength and Brinell hardness*

tion. In this case an indicating scleroscope was used for some of the work and a recording instrument for the remainder. The indicating instrument gave uniformly lower values than the recording type, so that the scleroscope values for the plates are not in all cases intercomparable. Those taken with the latter instrument are marked with an asterisk in Table 5, which gives the hardness values for both corners of each plate.

The method of heat treatment described in Section III–2 does not give exactly the same hardness to both the small tensile specimens and the relatively larger plates. To secure the same hardness, it would have been necessary to draw back the tensile specimens at varying temperatures until like conditions were reached.

By aid of Fig. 16, showing the relation between tensile strength and hardness for this class of steels, an idea of the actual tensile properties of the hardened plates may be obtained.

V. COMPARISON TESTS ON SIMILAR MATERIAL

In addition to the ingots prepared by the Bureau of Mines there was also available for study other material of a similar nature which was submitted through the Bureau of Ordnance of the Navy Department and was secured from one of the large automobile manufacturers who was constructing armored tanks during the war and whose representatives had made great claims for zirconium as an alloying element in light armor plate. This material consisted of 45 plates of ¼ to ½ inch thickness, representing 28 separate heats of steel. Each heat, comprising about 1000 pounds of metal, was made in an electric furnace.

The majority of the plates as submitted were 18 inches square. The following, however, were 12 inches square: 16–1, 19–1, 20–3, 22–2, 22–3, 22–4, 24–5, 25–1, 25–2, 25–4, 25–8, 27–3, and 27–4. (The first number in all cases refer to the heat number and the second to the plate number of that heat.) The plates were supposedly heat treated, but many were found to be soft and were heat treated at the Bureau of Standards in accordance with a summary of the heat treatments given the same material by the manufacturer.

All plates were cut up, the hardened ones by grinding, so as to produce two tensile bars, an impact specimen, and a 12 by 12 inch ballistic plate from the large size plates. From the smaller plates a ballistic plate of 11 by 11 inches was obtained in most cases.

In Table 7 is given the heat treatment of the plates and test pieces on those plates which were heat treated at the Bureau of Standards.

The same type of specimen and testing procedure was used for these materials as for those described above, with the exception that the B and C specimens are both hardened and no tests were made on normalized material.

In Table 12 will be found the results of impact tests calculated in a similar manner to those given before.

A comparison of these tests made at the Bureau and those made by the manufacturer is given in Table 9, the average value for each heat being given. In the grand average certain of the heats are omitted, as noted in the table, since the figures from both sources are not strictly comparable.

TABLE 7.—Comparison Steels

[AC=Air cooled; FC=furnace cooled. All specimens drawn for one hour in oil bath unless otherwise stated]

Heat No.	Temperatures			Remarks	Heat No.	Temperatures			Remarks
	Normalizing	Quenching	Drawing			Normalizing	Quenching	Drawing	
	°C	°C	°C			°C	°C	°C	
2....	870 AC	850	205		18....	870 FC	850	190	
4....	870 AC	850	205		19....	816 AC	860	190	
6....	870 FC	850	205		20....	954 AC	850	316	Salt bath for drawing
8....	870 FC	850	193						
9....	870 AC	830	193		21....	870 FC	850	190	
					22....	870 FC	850	190	Drawn for three hours
10....	870 AC	830	193						
11....	870 FC	777	177		23....	870 FC	827	205	
12....	870 AC	843	205		24....	870 AC	860	205	
13....	870 FC	850	205						
14....	870 FC	843	288	Salt bath for drawing.	25....	900 FC	850	205	
					26.....	800 AC	800	200	
					27....	816 AC	843	204	
15....	870 FC	827	290	Do.	28[a]...	800 AC	800	200	
16....	870 FC	830	193						

[a] These values not given by manufacturer, but estimated at Bureau of Standards.

Table 10 gives the results of hardness measurements on ground portions of opposite corners of the plates. The results that were obtained on these comparison steels are quite similar to those obtained on our own material, but it will be noted that the highest tensile properties observed were not so great as those from the regular series. The comparison steels will therefore be included in the discussion of results and the effect of the various elements on the properties of steel.

TABLE 8.—Impact Tests (Izod Machine) of Comparison Steels

Steel	Diameter of spec.	Area at notch	Initial energy	Energy absorbed in breaking	
	Inch	Inch²	Ft.-lbs.	Ft.-lbs.	Ft.-lbs./in.²
2-1	0.449	0.1206	120	17.0	141
4-1	.397	.0815	100	6.0	74
6-1	.448	.1201	120	4.0	34
8-1	.399	.0827	100	12.0	145
9-1	.449	.1206	120	4.0	33
9-2	.400	.0833	100	3.5	42
10-2	.450	.1210	120	14.0	116
11-2	.400	.0833	100	14.0	168
12-1	.399	.0827	100	13.0	157
13-2	.499	.1206	120	6.0	50
14-1	.399	.0827	100	15.0	181
15-1	.400	.0833	100	6.0	72
16-1	.349	.0735	75	3.0	41
18-1	.450	.1210	120	15.0	124
19-1	.349	.0735	75	7.0	95
20-1	.348	.0733	75	5.5	75
20-3	.449	.1206	120	6.0	50
22-1	.349	.0735	75	8.0	109
22-2	.450	.1210	120	16.5	136
22-3	.449	.1206	120	9.0	75
22-4	.449	.1206	120	9.0	75
23-1	.349	.0735	75	9.0	123
24-5	.348	.0733	75	7.0	96
25-1	.398	.0821	100	11.0	134
25-2	.449	.1206	120	9.0	75
25-4	.398	.0821	100	10.5	128
26-1	.349	.0735	75	2.0	27
27-3	.301	.0549	60	4.0	73
27-4	.349	.0735	75	8.0	109
28-1	.450	.1210	120	4.0	33

TABLE 9.—Comparison Steels

[Comparison of Bureau of Standards and manufacturers' tests]

Kind of steel	Heat No.	Bureau of Standards' tests					Manufacturers' tests				
		Tensile strength	Yield point	Elongation in 2 inches	Reduction in area	Brinell hardness numeral	Tensile strength	Elastic limit	Elongation in 2 inches	Reduction of area	Brinell hardness numeral
		Lbs./in.²	Lbs./in.²	Per cent	Per cent		Lbs./in.²	Lbs./in.²	Per cent	Per cent	
Ni, Si, Zr	1	257 100	188 800	11.3	37.3	523	301 000	250 000	10.5	25.9	555
Ni, Si, Zr	2	228 800	202 900	9.6	35.3	436	272 000	231 000	10.5	31.5	477
Ni, Si, Zr, Co, Mo	3	288 600	229 500	7.8	26.2	589	304 000	264 500	11.8	33.8	567
Cr, V, Mo	4	253 200	238 500	.3	1.0	556	202 000	202 000	1.0	3.3	532
Ni, Si, Cr, Zr	5	308 800	247 900	8.8	20.1	615	285 000	263 000	2.0	6.4	555
Cr, V, Mo	[a] 6	237 200	209 900	2.3	4.1	540	(b)	(b)			600
Ni, Si, Zr	7	282.500	254 700	8.5	18.3	584	294 000	264 000	6.5	8.8	555
Ni, Si, Zr	8	245 000	202 800	8.6	29.0	440	265 000	210 000	16.5	16.5	512
Cr, V, Mo	9	186 500		5.1	.6	556	183 000		1.0	1.0	566
Ni, Si, Zr	10	285 600	259 400	7.8	31.5		225 000	200 000	10.0	36.0	532
Ni, Mo, Zr	11	208 700	187 800	7.8	28.6	324	202 500	176 500	13.5	46.5	444
Ni, Si, Cr, Zr	12	283 300	221 600	9.1	33.3	445	295 500	255 000	4.5	9.0	555
Ni, Si	[a] 13	172 700	(c)	(c)		545	284 000	250 000	10.0	30.0	578
Ni, Co, Si, Zr	14	325 400	268 300	8.5	19.8	534	281 000	238 000	10.3	32.0	545
Ni, Si, Co, Mo	[a] 15	226 700	(c)	(c)		509	260 000		1.0	5.0	578
Ni, Si, Zr	[a] 16	236 800	226 200	1.0	4.7	564	(b)	(b)			512
Ni, Si, Zr	[a] 17	(d)	(d)	(d)	(d)		272 500	233 500	8.5	27.0	477
Ni, Si, Zr	18	253 900	208 800	11.5	32.9	555	285 700	250 000	10.7	30.7	543
Ni, Cr, Si, Zr	19	262 600	227 800	1.5	3.3	567	287 000	250 000	3.0	5.0	555
Ni, Si, Zr	20	301 800	236 900	5.7	14.9	542	312 000	254 500	10.3	30.0	534
Ni, Si, Zr	21	252 500	245 800	10.0	28.4	424	270 000	235 000	12.5	44.0	512
Ni, Co, Si, Zr	22	277 900	238 100	8.7	38.4	512	290 000	245 000	11.0	43.0	512
Ni, Si, V	23	292 300	224 600	.1	3.4	512	326 000	270 000	7.8	16.0	534
Ni, Si, Zr	24	281 500	228 800	9.0	33.4	578	297 000	242 000	8.5	21.5	532
Ni, Si, Zr	25	303 600	245 100	9.5	30.7	600	309 000	245 000	10.5	29.0	544
Ni, Si, Zr	[a] 26	(c)	(c)			636	(e)	(e)			
Ni, Si, Zr	27	283 800	254 200	7.9	31.9	385	295 000	250 000	2.5	4.5	600
Ni, Si	[a] 28	(c)	(c)			593	(e)	(e)			
Average		269 700	230 600	7.5	23.5	514	275 300	239 800	8.3	22.6	536

[a] Values for these heats not included in average. [b] Broke in head. [c] Broke in shoulder. [d] Not tested in heat-treated condition. [e] No values given

TABLE 10.—Comparison Steels

[Hardness of plates on opposite corners]

Plate No.	Hardness numeral				Plate No.	Hardness numeral			
	Brinell		Sclero-scope			Brinell		Sclero-scope	
1–3	532	495	61	[a] 60	17–1	262	262	29	[a] 30
2–1	418	402	49	47	18–1	512	526	60	62
2–2	375	387	44	[a] 45					
3–1	607	532	62	[a] 61	18–2	273	277	32	[a] 5
4–1	510	495	53	51	19–1	486	522	58	
					19–2	293	293	32	[a] 33
4–2	311	311	38	[a] 38	20–1	504	516	56	57
5–1	600	546	57	[a] 55	20–3	514	571	57	66
5–2	600	600	65	[a] 65					
6–1	555	578	63	67	21–1	474	470	58	56
6–2	477	495	55	[a] 57	22–1	514	479	61	58
					22–2	553	512	67	55
7–1	600	555	58	[a] 55	22–3	495	474	58	47
7–2	512	495	62	[a] 60	22–4	474	465	47	44
8–1	474	452	53	52					
9–1	560	555	66	65	23–1	571	544	72	68
9–2	555	568	61	63	24–5	532	483	64	58
					25–1	522	518	56	55
10–2	508	512	57	63	25–2	529	553	59	61
11–2	418	418	56	53	25–4	510	526	57	61
12–1	509	512	65	67					
13–1	258	262	33	[a] 35	25–8	544	550	65	67
13–2	567	522	66	64	26–1	562	562	71	69
					27–3	407	446	47	48
14–1	504	500	66	59	27–4	439	452	53	54
15–1	512	486	60	59	28–1	522	480	60	54
16–1	477	460	50	49					

[a] Plates not heat treated at Bureau.

VI. EFFECT OF VARIOUS ADDITION ELEMENTS

The large number of steels examined offers an excellent opportunity for studying the effects of the various alloying elements. In nearly all the heats, however, the silicon content is higher than that usually obtained in ordinary practice. For purposes of comparison it is necessary to classify the steels into groups having the least possible number of variables in each group. The carbon content is a variable in practically every group, and the arrangement given in the tables is according to increasing carbon content.

The groups into which the steels have been roughly classified are as follows: Group A, silicon steels; Group B, nickel-silicon steels; Group C, silicon-zirconium steels; Group D, nickel-silicon-zirconium steels; Group E, cerium steels; Group F, copper steels; Group G, boron steels; Group H, uranium steels; Group I, molybdenum steels; Group J, nickel-chromium steels; Group K, vanadium steels; Group L, chromium-tungsten steels; Group M, cobalt steels.

1. GROUP A—SILICON STEELS

This group, shown in Table 11, represents plain carbon steels in which the silicon is greater than normal and which have all been deoxidized with aluminum. The group has been further divided into steels that have greater or less than 1 per cent silicon. It will be noted that the increase of silicon to above 1 per cent has resulted in a greater tensile strength and impact value without materially reducing the ductility. Nos. 1269 and 1270, containing, respectively, 0.65 per cent titanium and 0.45 per cent aluminum, show no superiority over No. 1104, which is simply deoxidized with these elements.

2. GROUP B—NICKEL-SILICON STEELS

Table 12 illustrates this group which has been further classified into steels containing 2 per cent nickel, 3 to 3.25 per cent nickel with silicon greater or less than 1 per cent, and those having more than 3.25 per cent nickel.

The class with 2 per cent nickel all contain approximately 1 per cent silicon and show increased mechanical properties in comparison with the corresponding class of Group A. A few steels in this class have tensile strength in the neighborhood of 300 000 lbs./in.^{2}, but the ductility and toughness are not as great as in those that follow.

The 3 per cent nickel group again shows the advantage of increasing the silicon to greater than 1 per cent. In fact, this combination of elements represents about the best of any of those tested, the majority having a tensile strength from 270 000 to 315 000 lbs./in.^{2}, depending upon the carbon content, yield point from 200 000 to 250 000 lbs./in.^{2}, and proportional limit from 100 000 to 160 000 lbs./in.^{2}, excellent ductility and satisfactory impact values. The values for the normalized steels are also excellent. A carbon content of from 0.40 to 0.50 seems to be the most favorable.

The nickel content apparently should be kept in the range 3 to 3.25 per cent, as those steels having a higher percentage than this were nearly all brittle.

Group B also shows, as did Group A, that aluminum and titanium in amounts greater than that needed for deoxidation offer no advantage and, in fact, appear to be in most cases detrimental.

3. GROUP C—SILICON-ZIRCONIUM STEELS

This group as tabulated in Table 13 should be compared with Group A, which contains similar steels without zirconium. The zirconium content is variable from a small amount to 0.60 per cent. A study of Tables 11 and 13 seems to indicate that in the steels of lower carbon content the zirconium may have increased the ductility but not the tensile strength for the heat-treated steels. In the higher carbon range the ductility is much less than for similar steels in which zirconium is absent. The normalized steels containing zirconium have lower proportional limit, yield point, tensile strength, and ductility than those of Group A.

4. GROUP D—NICKEL-SILICON-ZIRCONIUM STEELS

These steels shown in Table 14 are subclassified similar to those of Group B. The 2 per cent nickel steels do not give as great tensile strength with zirconium as without it, but seem to show greater ductility and toughness. The same may be said of the 3 per cent nickel steels, although in this case the ductility is not increased to as great an extent, if any. There are several places in the table where the carbon content is constant and zirconium practically the only variable. None of these instances, however, show any regular effect on the properties attributable to the zirconium content.

5. GROUP E—CERIUM STEELS

The cerium steels without nickel, as shown in Table 15 and compared with the first portion of Group H, indicate that with about 0.25 per cent of cerium the tensile properties are increased with accompanying loss of ductility. The nickel-cerium steels have been arranged partly in order of cerium content in the table, since they are all of approximately the same carbon content. Although nearly all of the nickel-cerium steels have the nickel-silicon ratio shown in Group B to be desirable, it also appears that small amounts (up to 0.10 per cent) of cerium are beneficial, while larger quantities offer no further advantage. No. 1260, with only 0.01 per cent cerium, is a most excellent steel.

The rôle of cerium is thought to be that of a desulphurizer, and in Nos. 1256 and 1257 the sulphur content was intentionally increased to investigate this point. The tensile strength of these two steels is quite high, but the ductility is less than would be expected from a consideration of the other constituents. In amounts over 0.30 per cent cerium segregates very badly, and accordingly it would appear preferable to keep it below this figure.

6. GROUP F—COPPER STEELS

The copper has been added to these steels in place of a portion of the nickel content, and an inspection of Table 16 indicates that in those steels in which the sum of the nickel and copper, together with the silicon and carbon, are in the favorable ratio the usual high tensile strengths are secured, but with a reduction of the ductility and toughness. Specimens Nos. 1279 and 1280, for instance, broke in the shoulders, while the impact values are mostly low. No. 1285, with 0.70 per cent zirconium, apparently corrected for some of the lost ductility.

7. GROUP G—BORON STEELS

This group can almost be dismissed from further consideration because of manufacturing difficulties in producing sound steel containing boron. The majority of the steels (see Table 17) were of low carbon content, but do not compare favorably with similar steels of Groups H and B. The ductility is in all cases low even with small amounts (0.02 per cent) of boron. No. 1276, containing the favorable ratio of carbon, silicon, and nickel, did not show the high properties for that class.

8. GROUP H—URANIUM STEELS

There were only three steels containing uranium—Nos. 1228, 1229, and 1244—all having the favorable ratio of carbon, silicon, and nickel except No. 1228, which carried 0.63 per cent carbon. No 1244 showed the usual high properties, but the other two were less desirable (see Table 22).

9. GROUP I—MOLYBDENUM STEELS

With the possible exception of Nos. 3, the molybdenum steels (see Table 18) do not show the remarkable ductility claimed elsewhere for this element.[5]

This may, of course, be due to type of heat treatment to which all of these steels were subject, but it is probable that all of the steels in the nickel-molybdenum series would have been superior for the purpose desired with the molybdenum omitted.

[5] Molybdenum as an alloying element in structural steels, G. W. Sargent, Proc. Am. Soc. for Test. Mats. 20, Part II, p. 5; 1920.

10. GROUP J—NICKEL-CHROMIUM STEELS

The nickel-chromium steels classified in Table 19 all show good properties particularly regarding ductility and toughness. Although most of the steels contain zirconium also, the previous considerations would not indicate that this element has greatly influenced the results. The properties of all of the steels in Group J could be reproduced without the addition of either chromium or zirconium.

11. GROUP K—VANADIUM STEELS

This group contains the steel (No. 1207) which showed the highest tensile strength observed in the entire investigation—about 344 000 lbs./in.^{2}. Although the ductility is not so great as in certain of the other steels having very high tensile strength, it is nevertheless considerable for such a steel. In passing it might be worthy of mention that from a portion of the plate from this heat was constructed a spring for a precision aeronautic altimeter. This spring is constantly operating under a computed maximum fiber stress of 100 000 lbs./in.^{2} and shows no elastic hysteresis or aftereffect, which is common to springs in such instruments. The group, as a whole, shows good properties but can not be considered as preferable to Group B (see Table 20).

12. GROUP L—CHROMIUM-TUNGSTEN STEELS

This group, consisting only of Nos. 1177 and 1178, comprises too small a number to permit drawing any conclusions, but apparently offers no particular advantages (see Table 22).

13. GROUP M—COBALT STEELS

The steels in this group (Table 21) are all from the comparison series. All except No. 15, which contained molybdenum in addition, showed high tensile strength, with good ductility and toughness. It is probable that cobalt acts similarly to copper in replacing some of the nickel.

TABLE 11.—Group A—Silicon Steels

LESS THAN 1 PER CENT SILICON

No.	Composition					Normalized							Heat treated							
	C	Si	Mn	Al	Ti	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1269....	0.36	0.55	0.64	0.06	0.65	.....	48 100	81 200	30.0	57.4	160	28	.....	113 000	129 400	10.6	29.1	195	30	120
1270....	.38	.46	.52	.45	.....	43 000	.....	89 600	26.3	50.2	163	24	42 000	.....	111 200	9.5	30.6	.....	28	128
1104....	.39	.66	.58	.01	.03	52 000	61 500	95 400	25.0	46.0	178	27	30 000	56 000	126 000	11.0	26.3	187	26	.....
MORE THAN 1 PER CENT SILICON																				
1198....	0.24	1.10	0.71	0.01	.....	58 000	61 200	87 300	22.5	59.0	178	28	.....	57 400	99 700	12.5	51.5	185	18	625
1199....	.27	1.10	.75	.01	.....	.....	68 500	94 100	21.5	59.0	196	28	40 000	68 100	105 000	17.0	52.0	207	19	460
1102....	.36	1.15	.65	.03	0.06	40 000	60 400	102 900	23.0	51.5	190	26	40 000	75 000	156 500	8.0	13.1	188	25	.....
1163....	.38	1.40	.81	.01	.....	51 000	64 000	102 000	19.5	53.7	207	21	61 000	.....	145 400	2.0	22.1	255	24	246
1201....	.41	1.25	.74	.02	.....	62 000	69 900	105 300	19.0	48.1	209	28	45 000	85 400	121 900	15.0	53.8	235	31	218
1164....	.42	1.50	.86	.01	.....	79 000	85 900	122 500	20.0	51.5	241	24	137 000	.....	259 400	4.5	15.9	418	59	109
1200....	.60	1.20	.74	.01	.....	65 000	90 800	133 400	15.0	45.1	269	19	105 000	.....	230 600	1.0	4.8	364	33	121

TABLE 12.—Group B—Nickel-Silicon Steels

2 PER CENT NICKEL

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1202....	0.25	0.95	0.61	2.00	0.02	.....	56 000	70 700	94 300	19.0	54.7	191	19	52 000	84 900	127 000	7.0	39.6	255	20	340
1174....	.40	1.23	.90	2.10	.02	0.27	.....	77 600	109 300	21.5	54.4	217	31	56 000	108 400	158 100	7.5	21.1	286	34	133
1165....	.41	1.50	.76	2.05	.01	.....	71 000	91 900	130 200	19.5	50.4	228	36	155 000	.....	294 200	3.5	9.2	321	35	79
1166....	.42	1.35	.80	2.05	Tr.	.....	81 000	88 600	121 400	21.0	54.4	240	32	132 000	.....	261 600	3.0	7.3	418	33	110
1167....	.54	1.25	.75	2.15	.01	.....	49 000	84 800	131 400	17.5	45.2	418	28	170 000	.....	316 700	4.0	16.0	340	30	61
1246....	.56	1.00	.90	2.15	N. D.	.44	.....	.....	115 100	4.0	7.9	286	38	.....	.....	192 800	1.0	.6	600	49	46
1245....	.57	1.85	.94	2.20	Tr.	.....	123 000	125 000	172 500	10.5	20.2	322	50	154 000	262 600	322 700	2.0	2.0	652	74	05
3 TO 3.25 PER CENT NICKEL, LESS THAN 1 PER CENT SILICON																					
1120....	0.44	1.00	0.97	3.15	0.01	.....	35 000	.....	178 500	4.5	4.0	302	30	126 000	.....	286 000	2.5	2.7	537	52	.....
1242....	.45	.65	.81	3.00	.06	0.60	56 000	80 900	136 200	15.0	30.0	255	32	155 000	185 750	275 900	5.5	14.1	512	55	88
28.....	.48	.90	.80	3.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	.....	33
1114....	.49	.52	.65	3.25	.02	.03	67 100	.....	117 200	11.3	18.9	241	35	170 000	.....	286 000	.6	1.1	444	36	.....
1113....	.51	1.00	1.10	3.20	Tr.	.35	.....	.....	.....	.....	.....	.....	.....	63 000	.....	194 500	1.0	2.1	375	28	.....

3 TO 3.25 PER CENT NICKEL, MORE THAN 1 PER CENT SILICON

1171....	0.26	1.35	0.78	3.00	0.01	.....	49 000	81 000	137 600	23.0	54.1	228	23	116 000	.....	232 200	6.0	37.2	382	49	134
1168....	.35	1.35	.77	3.05	.01	.....	44 000	90 800	122 500	19.0	48.3	444	43	134 000	.....	268 900	6.5	15.4	364	29	99
1129....	.36	1.15	.85	3.20	.01	.....	40 000	80 600	137 300	13.1	27.1	241	28	90 000	.....	275 100	8.0	22.9	402	37	.....
1214....	.39	1.40	.77	3.10	Tr.	.....	39 000	105 800	127 300	19.0	45.1	268	28	143 000	231 000	282 200	10.0	36.6	564	47	88
1128....	.40	1.10	.86	3.20	.01	.....	50 000	82 000	138 500	4.5	20.0	249	31	140 000	.....	276 000	7.5	25.5	488	51	.....
1130....	.40	1.20	.90	3.20	.02	0.33	72 500	87 100	166 900	8.0	8.6	241	32	130 000	196 000	272 000	15.0	26.1	512	53	.....
1251....	.40	1.25	1.46	3.15	.01	.....	41 000	83 000	191 100	1.5	3.4	450	57	102 000	.....	286 700	1.0	2.0	587	68	37
1238....	.40	1.25	1.99	3.00	Tr.	.....	.....	.....	.....	.....	.....	.....	.....	145 000	279 300	292 700	9.5	31.3	578	46	84
1204....	.40	1.45	.86	3.00	.02	Tr.	.....	107 500	141 500	11.0	30.3	269	22	145 000	264 100	292 200	10.5	38.5	502	36	100
1227....	.40	1.45	.84	3.10	.01	.....	52 000	97 000	133 800	18.5	52.0	266	41	165 000	204 700	285 900	8.5	38.9	555	52	74
1236....	.40	1.45	1.10	3.00	Tr.	.....	.....	145 200	192 700	8 0	9.8	368	44	110 000	255 000	289 700	8.5	35.6	564	45	116
1226....	.40	1.60	.90	3.05	Tr.	.....	45 000	96 900	138 900	14.0	42.3	289	35	.....	251 400	282 800	9.5	32.9	555	69	83
1169....	.42	1.35	.82	3.10	Tr.	.....	76 000	96 150	136 600	19.5	47.3	255	36	152 000	.....	262 100	1.0	1.6	555	59	75
1147....	.43	1.05	.81	3.10	.33	.....	60 000	.....	240 200	4.0	11.5	300	30	136 000	.....	287 400	6.5	22.8	387	32	.....
1216....	.43	1.25	.82	3.00	.12	.45	.....	122 200	136 900	17.5	34.4	255	25	.....	205 900	250 800	6.0	14.9	444	33	112
1206....	.45	1.25	.81	3.15	.23	.....	45 000	90 000	132 000	20.0	48.4	277	25	.....	267 000	303 000	11.0	34.8	546	44	129
1205....	.48	1.35	.71	3.00	.02	.01	65 000	93 600	130 900	17.5	47.3	271	25	150 000	288 600	314 700	5.5	11.1	564	46	95
1215....	.49	1.30	.78	3.05	Tr.	.....	53 000	92 300	128 900	21.0	53.3	266	26	145 000	232 500	296 500	7.5	12.9	591	56	50
1237....	.49	2.20	.94	3.05	Tr.	.....	72 000	108 000	155 600	14.5	40.9	317	45	.....	258 100	312 600	8.0	24.9	532	46	61
1217....	.52	1.10	.80	3.05	.17	.45	50 000	89 000	134 100	15.5	42.9	289	28	160 000	251 100	315 200	7.0	20.3	564	37	88
1170....	.52	1.25	.79	3.00	Tr.	.....	71 000	99 000	145 600	16.5	41.3	286	37	.....	.....	.....	.....	.....	.....	.....	61
1208....	.53	1.25	.97	3.10	.01	.....	55 000	102 700	148 200	12.5	30.6	302	27	130 000	.....	206 500	.5	2.0	600	53	38
1209....	.74	1.20	1.13	3.10	Tr.	.....	49 000	131 300	155 200	5.5	30.2	302	46	.....	.....	.....	.....	.....	627	81	20

3.25 TO 3.50 PER CENT NICKEL

1172....	0.24	1.30	0.76	3.30	Tr.	.....	44 000	77 100	112 600	23.5	54.2	228	33	121 000	.....	224 100	8.5	32.6	387	42	148
13.....	.45	1.65	1.01	3.49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	50
1113....	.55	1.15	.76	3.55	0.03	0.03	74 000	90 000	132 400	6.5	11.6	284	43	.....	.....	235 000	.25	.7	509	42	.....
1239....	.58	1.50	.96	3.50	Tr.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	19

[a] Broke in shoulder.

TABLE 13.—Group C—Silicon Steels with Zirconium

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1184	0.23	1.30	0.61	Tr.	0.05	0.25	28 000	45 000	79 300	28.5	60.8	179	24	23 000	62 400	99 140	23.5	55.0	187	22	237
1185	.26	1.35	.71	Tr.	T .08 / B .05	.50 / .30	50 000	63 500	92 200	28.0	65.9	179	17	36 000	54 800	97 100	20.5	54.7	387	28	352
1180	.33	1.55	.63	Tr.	.10	.50	32 000	48 000	92 500	22.5	51.5	189	27	35 000	.....	135 600	9.0	30.1	228	27	116
1181	.34	1.70	.69	Tr.	.07	.60	.....	62 100	100 700	24.5	53.7	207	30	.....	91 900	140 400	12.5	26.8	187	31	124
1183	.36	1.70	.77	Tr.	.06	.22	43 000	.....	106 800	24.5	53.0	206	17	90 000	.....	192 600	4.0	19.8	286	35	82
1107	.37	.73	.50	0.02	.03	.20	30 000	50 500	95 000	10.0	22.8	179	27	24 000	.....	99 500	9.5	21.3	196	25	.....
1182	.42	1.55	.76	Tr.	.03	.03	47 000	76 500	115 400	19.0	52.3	212	29	75 000	128 300	148 800	1.5	32.0	269	31	126
1106	.42	.44	.55	.13	.01	.15	39 000	53 250	101 000	8.0	20.3	196	25	126 000	206 000	236 000	1.5	4.5	509	54	.....
1103	.45	.50	.67	.02	.02	.03	42 000	.....	99 000	19.5	39.8	185	27	54 000	.....	164 500	5.0	8.5	241	27	.....
1109	.47	.85	.78	.15	.02	.11	31 000	.....	110 800	16.0	22.7	207	31	50 000	.....	147 500	.5	2.2	292	28	.....
1101	.51	1.15	.80	.09	.04	.10	53 000	.....	115 400	16.0	38.6	228	29	80 000	.....	262 000	1.5	2.0	520	44	.....
1105	.56	.54	.75	.07	.02	.09	50 000	56 000	100 700	11.0	18.7	197	27	.....	.....	202 750	.25	.0	454	43	.....

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium

2 PER CENT NICKEL

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1186..	0.26	1.35	0.74	2.00	Tr	0.06	0.25	35 000	.....	110 000	14.5	44.4	207	25	90 000	.....	206 800	8.5	40.3	418	.....	163
1192..	.26	1.50	.76	2.05	Tr	.15	T. 80 B. 35	30 000	62 000	95 600	19.5	57.3	212	26	35 000	89 000	125 300	10.0	40.3	255	24	202
1187..	.29	1.40	.67	2.00	Tr	.07	T. 38 B. 27	42 000	68 400	96 200	28.5	56.1	194	31	67 000	148 900	180 500	4.0	39.3	382	47	122
1193..	.29	1.45	.67	2.05	Tr	.20	.30	49 000	77 000	97 900	23.0	54.3	219	28	46 000	.....	133 700	9.0	41.3	241	32	236
1191..	.32	1.40	.77	2.10	Tr	.09	.40	34 000	77 100	106 800	21.5	54.7	226	29	.....	172 800	201 200	2.5	11.7	306	34	101
1190..	.33	1.45	.70	2.15	Tr	.07	.45	.....	77 400	106 100	22.5	49.3	217	25	.....	148 500	180 200	2.0	24.0	364	33	120
1249..	.35	.46	.62	1.75	0.07	.04	.60	61 000	75 500	103 000	22.0	54.7	216	30	39 000	127 300	143 400	16.5	38.2	289	32	136
1248..	.35	2.00	.76	1.60	.14	.04	.55	51 000	87 300	116 600	21.0	50.1	286	36	.....	98 600	175 300	7.0	23.4	340	43	81
1161..	.38	1.20	.75	2.15	.06	.01	.08	73 000	78 600	115 900	21.0	46.0	228	21	123 000	.....	247 500	4.0	32.2	390	44	.....
1176..	.43	1.10	.87	2.00	.17	.11	.13	61 000	86 900	139 600	19.5	44.9	255	31	166 000	.....	293 700	7.0	24.1	477	37	108
27....	.43	1.26	.71	2.16	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	146 200	254 200	283 800	7.9	31.9	385	43	91
1175..	.45	1.45	.97	2.10	.12	.15	.10	49 000	.....	127 600	24.5	42.3	266	32	126 000	.....	282 100	5.5	11.7	444	35	88
1162..	.51	1.25	.66	2.10	.06	.01	.10	34 000	70 000	113 200	18.5	32.7	288	21	73 000	184 700	245 600	33.5	10.7	351	37	51

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium—Continued

3 PER CENT NICKEL, LESS THAN 1 PER CENT SILICON

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1222..	0.33	0.23	0.51	3.00	0.04	0.01	0.07	.....	74 200	95 700	22.5	47.3	183	25	137 000	223 800	239 700	8.5	32.4	387	55	91
1212..	.34	.80	.65	3.05	Tr	.04	.40–.20	42 000	65 500	106 000	24.0	41.7	207	30	100 000	212 500	221 500	10.5	35.6	450	56	100
1223..	.36	.30	.57	3.00	.08	.01	.07	60 000	73 600	106 200	20.0	52.2	196	26	136 000	243 600	269 700	8.5	29.5	324	36	79
1233..	.36	.27	.57	3.05	.02	.01	.16	.....	71 400	103 000	21.5	53.4	265	28	.....	207 600	245 300	8.5	31.9	500	57	74
1240..	.37	.65	.70	3.00	.02	.01	.12	.....	92 400	156 900	6.5	23.8	266	.....	137 000	203 300	273 700	8.5	28.9	512	67	120
1224..	.38	.95	.45	3.05	Tr	.10	.20	60 000	83 700	106 800	24.0	50.5	418	20	63 000	146 800	175 000	8.5	14.8	340	26	101
1243..	.40	.95	.85	3.00	.01	.02	.15	38 000	173 000	200 600	6.5	16.0	324	30	146 000	249 100	281 800	10.0	38.3	546	55	138
1213..	.40	.80	.65	3.15	Tr	.04	.33	42 000	73 000	112 300	20.5	40.9	241	22	150 000	209 800	276 500	6.0	20.8	546	41	38
1232..	.42	.20	.48	3.00	.01	Tr	.11	38 000	67 700	100 300	22.0	48.3	199	27	141 000	228 200	256 100	8.5	32.2	550	63	74
1115..	.43	.20	.73	3.15	Tr	Tr	.05	72 000	.....	121 000	16.5	40.2	210	26	62 000	.....	170 000	5.0	11.6	354	32	.....
1231..	.43	.76	.81	3.00	.05	.02	.15	59 000	148 900	188 900	3.0	18.4	269	34	.....	211 600	290 100	9.5	36.7	546	48	109
1119..	.44	.85	.92	3.15	.01	.01	.05	53 000	100 000	198 000	2.5	33.2	321	35	120 000	.....	297 000	7.0	18.5	546	56	.....
1158..	.44	.75	.73	3.10	.16	.03	.21	47 000	138 200	140 200	8.0	23.2	447	25	172 000	.....	287 000	6.0	17.8	387	42	46
1111..	.46	.27	.59	3.15	.03	.01	.03	77 000	82 200	110 500	17.5	37.3	216	30	95 700	.....	271 000	.7	1.2	438	37	.....
26....	.48	.93	.96	3.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	.....	.....	.....	.....	.....	27
24....	.48	.57	.81	3.18	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	150 000	226 800	281 500	9.0	33.4	578	66	96
20....	.54	.95	.72	3.19	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	121 700	236 900	301 800	5.7	14.9	542	67	75
1241..	.61	.67	.75	3.05	.01	.02	.10	46 000	112 100	145 800	10.0	37.7	269	33	.....	260 300	290 300	3.0	2.7	591	79	28
1230..	1.53	.22	.70	3.00	.04	.04	.08	81 000	100 300	151 400	5.0	11.0	298	42	.....	.....	.....	.....	.....	600	73	10
3 PER CENT NICKEL, MORE THAN 1 PER CENT SILICON																						
1189..	0.27	1.50	0.73	3.15	Tr.	0.04	0.20	44 000	.....	116 100	20.0	44.4	241	33	110 000	216 000	221 600	18.0	26.8	321	24	109
1188..	.27	1.40	.74	3.15	Tr.	.06	.32	57 000	74 300	100 400	24.5	55.3	197	24	80 000	189 600	199 400	10.0	40.9	344	26	136

1235..	.28	1.45	.46	2.95	0.02	.06	.60	38 000	67 700	110 300	27.5	53.0	216	34	53 000	142 000	154 100	7.0	42.1	.....	39	183
1197..	.32	1.50	.60	3.05	.01	.16	.33	52 000	79 000	109 800	22.5	52.8	228	31	85 000	189 200	217 100	3.0	27.5	321	37	116
1195..	.32	1.50	.65	3.00	Tr.	.07	.50	46 000	84 900	111 100	12.0	15.6	248	30	95 000	.....	187 200	2.0	3.9	382	44	102
1196..	.32	1.50	.65	3.05	Tr.	.13	.55	68 000	82 000	109 200	23.5	52.3	223	33	95 000	217 900	229 600	7.5	36.9	382	39	130
1211..	.32	1.10	.96	3.10	Tr.	.07	T .80 B .35	.....	119 000	140 400	9.0	10.5	279	31	138 000	221 000	237 500	8.0	34.3	488	.....	130
1134..	.34	1.30	.93	3.15	.01	.01	.15	25 500	.....	201 500	5.5	66.5	269	33	140 000	.....	281 000	11.0	13.6	555	58	.....
2.....	.34	1.32	.82	2.60	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	111 000	202 900	228 800	9.6	35.3	436	60	141
1219..	.34	1.35	.38	3.10	.02	.15	.70	48 000	64 900	100 400	24.0	55.6	217	22	.....	129 900	152 800	12.0	33.6	248	22	146
1210..	.34	1.10	.57	3.05	Tr.	.06	.55	60 000	78 900	107 900	22.0	44.7	234	37	106 000	218 000	232 200	6.5	36.5	351	27	117
1290..	.35	2.00	.86	3.00	.14	.03	.40	60 000	150 300	172 100	16.5	20.8	307	38	90 000	216 300	232 000	5.5	12.9	420	48	82
1221..	.36	1.00	.61	3.10	.10	.45	.16	44,000	74 000	110 800	24.0	50.6	228	32	62 000	130 200	173 600	10.0	28.2	319	47	121
21.....	.36	1.01	.82	3.14	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	152 500	245 800	252 500	10.0	28.4	424	62	.....
1194..	.36	1.40	.65	3.05	Tr.	.07	.45	.....	83 800	110 700	23.0	52.0	228	33	.....	229 600	246 600	6.0	34.0	375	46	88
1218..	.36	1.10	.38	3.00	.07	.35	T .80 B .30	60 000	82 600	109 000	23.0	50.6	302	28	.....	153 700	179 200	6.0	23.9	532	34	122
1225..	.37	1.15	.56	3.05	.02	.11	.20	.....	82 200	111 300	21.5	53.3	241	33	130 000	230 900	251 700	4.5	30.3	532	45	116
1293..	.37	1.15	.83	3.20	.02	.02	.05	47 000	142 800	159 900	5.5	22.6	268	38	.....	263 400	284 800	8.5	26.5	454	47	95
1144..	.38	1.35	.84	3.10	.01	.02	.31	59 000	.....	220 200	5.0	5.2	386	23	125.000	.....	307 600	7.5	21.7	436	40	.....
1157..	.39	1.20	.75	3.10	.10	.02	.10	26 000	126 400	132 300	20.0	32.7	255	30	130 000	239 000	242 000	10.0	36.9	502	50	112
1131..	.39	1.05	.90	3.15	.01	.02	.12	54 000	.....	259 000	4.0	5.2	375	32	136 000	.....	267 500	1.0	4.5	512	39	.....
1132..	.39	1.10	.90	3.20	.01	.06	.20	50 000	.....	221 000	2.0	4.2	364	44	135 000	.....	290 600	4.0	8.4	555	43	.....
1145..	.41	1.20	.81	3.15	.10	.02	.14	53 000	.....	175 300	8.0	26.0	240	23	150 000	.....	271 800	7.5	31.9	418	29	.....
1.....	.41	1.65	.80	2.93	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	188 800	257 100	11.3	37.3	523	56	.....
1220..	.43	1.05	.70	3.00	.10	.40	.20	48 000	79 400	118 800	19.5	43.8	255	40	70 000	199 200	219 800	2.5	7.9	387	35	75
14.....	.43	1.56	1.08	3.01	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	175 000	268 300	325 400	8.5	19.8	534	64	181
1289..	.43	1.55	.83	3.02	Tr.	.03	.40	57 000	205 000	207 900	5.0	7.9	275	38	110 000	217 800	261 600	.0	14.1	396	52	95
1234..	.43	1.85	.70	2.95	.04	.08	.55	86 000	104 600	132 100	17.0	43.4	277	38	.....	237 600	259 000	5.0	12.2	555	69	88
1146..	.44	1.05	.84	3.20	.01	Tr.	.05	35 000	.....	207 100	5.5	13.4	384	25	.....	.....	.....	.....	.....	.....	.....	.....
1138..	.45	1.20	.84	3.10	Tr.	.01	.05	.....	93 400	143 300	14.0	32.2	277	33	.....	177 650	300 800	6.0	9.9	.....	.....	54
1112..	.46	1.10	.66	2.95	.09	.03	.08	50 000	84 000	100 600	11.0	27.5	241	34	.....	.....	296 800	3.5	.0	532	55	.....
25.....	.46	1.05	.93	2.74	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	144 100	245 100	303 600	9.5	30.7	600	68	112
1117..	.47	1.00	1.10	3.20	.01	.01	.07	76 000	.....	230 700	1.0	1.4	444	35	150 000	.....	280 200	2.0	4.1	555	47	.....

[a] Broke in shoulder.

TABLE 14.—Group D—Nickel-Silicon Steels with Zirconium—Continued

3 PER CENT NICKEL, MORE THAN 1 PER CENT SILICON—Continued

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1291..	0.47	1.25	1.00	2.90	0.08	0.02	0.22	.....	123 900	155 700	6.5	10.9	266	32	166 000	.....	234 300	0.0	0.7	491	52	75
1292..	.48	1.78	.93	3.15	.01	.04	.06	57 000	106 800	154 800	18.5	24.3	268	35	150 000	.....	286 100	1.5	1.3	402	47	75
1160..	.50	1.20	.89	3.15	.05	.01	.10	44 000	.....	161 400	0.5	.0	364	32	147 000	.....	216 800	.5	2.0	516	50	.....
1159..	.51	1.20	.72	3.00	.04	.01	.25	60 000	.....	195 200	4.0	11.6	255	20	118 000	.....	291 200	3.0	4.0	440	36	.....
1247..	.54	2.45	.85	2.90	.01	.06	T .85 B .71	68 000	106 600	154 300	8.0	21.9	321	35	.....	.....	.....	.....	.....	.....	.....	54
MORE THAN 3.25 PER CENT NICKEL AND MORE THAN 1 PER CENT SILICON																						
1250..	0.15	1.55	0.95	3.55	0.01	0.03	T .65 B .35	39 000	96 900	133 400	15.5	49.3	286	41	.....	142 000	156 600	8.5	46.3	320	41	102
11....	.19	.47	.36	7.86	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	110 000	187 800	208 700	7.8	28.6	324	50	168
8.....	.37	2.16	1.14	3.64	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	125 800	202 800	245 000	8.6	29.0	440	62	145
17....	.38	1.39	.89	3.25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	(a)	(a)	(a)	(a)	.....	.....	.....	.....
7.....	.39	1.82	.77	3.33	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	98 500	254 700	282 500	8.5	18.3	584	61	.....
1133..	.39	1.65	.75	3.30	.01	.02	T .70 B .30	46 500	.....	148 500	12.0	31.9	262	33	136 000	.....	292 000	7.0	14.8	512	55	.....
16....	.39	1.59	.78	3.35	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	130 000	226 200	286 800	1.0	4.7	564	62	41
18....	.41	1.56	1.01	3.40	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	112 500	202 800	253 900	11.5	32.0	555	41	124
10....	.48	1.16	.88	3.45	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	123 000	259 400	285 600	7.8	31.5	.....	.....	116

[a] Not tested in heat-treated condition.

TABLE 15.—Group E—Cerium Steels

WITHOUT NICKEL

No.	Composition					Normalized							Heat treated							
	C	Si	Mn	Ni	Ce	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1268.....	0.39	0.75	0.68	.....	0.20	37 000	56 600	93 600	6.3	5.4	163	17	85 000	.....	128 200	.....	0.7	418	32	72
1272.....	.40	.27	.69	.....	.35	27 000	71 200	84 700	8.5	31.1	185	25	120 000	.....	188 900	.....	10.0	248	33	128
WITH NICKEL																				
1260.....	0.45	1.30	0.71	2.95	0.01	.....	134 300	143 900	15.6	40.8	269	24	.....	206 500	311 100	8.5	37.2	555	52	72
1256.....	.41	1.70	.73	2.80	.06	60 000	.....	143 400	7.5	37.6	285	39	175 000	244 900	298 000	7.5	7.2	555	58	174
1257.....	.46	1.55	.98	2.90	.10	54 000	103 200	176 300	9.5	5.4	321	41	184 000	235 000	312 100	4.6	7.3	.....	66	72
1259.....	.42	.80	1.15	2.95	T .31 B .19	53 000	80 000	127 300	21.0	17.8	217	37	65 000	149 000	202 500	8.6	10.4	228	57	97
1252.....	.44	1.30	.91	3.00	T .55 B .35	....	142 600	158 600	5.5	17.3	302	36	83 000	288 900	324 800	5.5	11.0	600	51	252
1258.....	.39	.25	.90	2.65	T 1.35 B .66	50 000	74 000	109 100	7.6	16.0	187	34	91 000	154 500	177 500	2.5	2.1	.....	.....	68
1253.....	.74	1.25	.82	2.25	T .22 B .07	100 000	115 300	171 000	10.5	36.1	359	48	.....	(a)	(a)	.....	.....	.....	.....	47
1281.....	.51	1.35	1.04	2.90	.03 Cu. 62	70 000	.....	154 300	1.0	.....	396	40	140 000	.....	251 700	1.0	14.1	530	52	33

[a] Broke in shoulder.

TABLE 16.—Group F—Copper Steels

No.	Composition								Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Ti	Zr	Cu	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
														Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1285...	0.35	1.40	0.76	2.55	0.02	Tr.	0.70	0.62	43 000	133 100	152 700	10.0	23.8	286	29	100 000	233 300	248 000	7.5	20.8	402	55	83
1282...	.45	1.10	.84	1.90	Tr.	.....	.....	1.35	80 000	128 200	150 800	11.0	27.2	320	37	.....	273 400	313 300	7.5	36.6	546	57	58
1286...	.46	1.30	.82	2.55	Tr.	.....	.....	.64	70 000	134 300	143 700	12.0	38.1	292	38	186 000	279 100	327 900	4.5	7.9	555	63	66
1280...	.49	1.25	1.03	2.45	.01	.....	.....	.55	55 000	171 800	173 600	6.0	14.8	326	35	150 000	.....	202 200?	.....	.....	550	60	50
1283...	.50	1.25	.78	2.60	.01	.....	.....	.36	85 000	131 500	147 500	12.0	44.7	285	38	.....	261 600	297 900	1.0	1.9	578	68	25
1281...	.51	1.35	1.04	2.90	.....	.....	.....	.62	70 000	.....	154 300	1.0	.....	396	40	140 000	.....	251 700	1.0	14.1	530	52	33
1279...	.58	.23	.90	2.45	.01	.....	.....	.62	71 000	131 500	139 700	11.5	19.7	279	37	140 000	.....	251 700?	.....	.7	642	70	34

TABLE 17.—Group G—Boron Steels

WITHOUT NICKEL

No.	Composition						Normalized							Heat treated							
	C	Si	Mn	Ni	Al	B	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
												Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1267.....	0.16	0.24	0.68	.....	0.06	0.39	.....	46 300	69 800	10.7	23.8	156	15	51 000	.....	96 100	3.9	19.1	217	30	37
1261.....	.21	1.50	.80	.....	.02	.57	54 000	58 000	84 600	11.5	25.6	217	.....	81 000	147 400	150 000	.5	9.8	555	43	48
1274.....	.45	.33	.69	.....	.03	.06	.....	84 800	100 500	17.0	41.7	187	23	.....	.....	85 400	.1	.7	387	52	36

WITH NICKEL

1278.....	0.16	1.20	0.84	3.00	0.02	0.09	40 000	.....	110 400	10.5	10.6	220	22	114 000	.....	170 900	0.8	2.7	387	38	161
1263.....	.18	1.30	.77	3.00	.02	.30	48 000	.....	65 800	14.0	5.4	196	21	112 000	.....	208 300	3.2	2.0	380	.....	48
1264.....	.19	.41	.67	3.05	Tr.	.50	55 000	65 000	90 700	10.8	20.8	175	.....	113 000	169 700	214 500	4.3	5.9	387	52	46
1277.....	.26	.36	.58	3.55	.....	.10	53 000	.....	160 900	12.0	46.8	205	24	135 000	205 100	226 700	2.3	7.9	470	60	109
1276.....	.47	1.25	.67	2.80	.02	.10	70 000	.....	120 600	17.0	31.1	262	35	100 000	244 900	256 300	3.0	7.9	425	55	35
1275.....	.69	.36	.50	2.90	.01	.08	57 000	132 900	139 900	11.0	22.6	285	34	170 000	.....	323 100	3.0	3.5	600	68	41

TABLE 18.—Group I—Molybdenum Steels

NICKEL-MOLYBDENUM

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Zr	Mo	Co	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
11	0.19	0.47	0.36	7.86	0.29	0.54	.....	.....	.....	.....	.....	.....	.....	.....	110 000	187 800	208 700	7.8	28.6	324	50	168
1135	.42	1.45	.83	3.25	.....	.78	.....	66 000	.....	146 000	23.0	25.9	286	35	83 000	.....	300 100	5.5	8.4	444	33	.....
1136	.44	1.80	.84	3.20	.....	.77	.....	37 500	.....	168 700	21.0	20.2	302	37	100 000	.....	257 700	6.5	12.2	393	36	.....
15	.43	1.28	1.09	3.45	.....	.70	0.38	.....	.....	.....	.....	.....	.....	.....	140 000	.....	226 700?	(a)	(a)	509	70	72
3	.44	1.46	.90	3.06	.37	.27	.59	.....	.....	.....	.....	.....	.....	.....	.....	229 500	288 600	7.8	26.2	589	69	.....

CHROME-MOLYBDENUM-VANADIUM

No.	C	Si	Mn	Mo	Cr	V														
9	0.34	0.22	0.87	0.84	1.30	0.28	.....	.....	.....	.....	.....	.....	.....	91 800	.....	186 500	5.1	0.6	556	68	38
4	.36	.14	.65	.22	1.14	.20	.....	.....	.....	.....	.....	.....	.....	127 500	238 500	253 200	.3	1.0	556	53	74
6	.51	.15	.75	1.45	1.08	.16	.....	.....	.....	.....	.....	.....	.....	105 000	209 900	237 200	2.3	4.1	540	71	34

[a] Broke in shoulder.

TABLE 19.—Group J—Nickel-Chromium Steels

No.	Composition							Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Zr	Cr	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
													Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1155....	0.38	0.16	0.48	3.60	0.07	0.10	1.14	50 000	198 400	201 700	7.0	28.2	444	41	134 000	257 700	258 600	7.5	29.5	532	57	113
12.....	.39	1.66	.99	3.54	.....	.25	.54	.....	.....	.....	.....	.....	.....	.....	123 500	221 600	233 300	9.1	33.3	445	58	157
5.....	.40	1.22	.84	3.34	.....	.28	.88	.....	.....	.....	.....	.....	.....	.....	.....	247 900	308 800	8.8	20.1	615	72	.....
1156....	.43	.85	.70	3.55	.02	.....	1.13	113 000	.....	198 900	1.5	1.4	512	61	153 000	.....	290 400	6.0	11.5	578	51	42
19.....	.43	1.50	.95	3.31	.10	.25	.60	.....	.....	.....	.....	.....	.....	.....	140 000	227 800	262 600	1.5	3.3	567	72	95

TABLE 20.—Group K—Vanadium Steels

No.	Composition					Normalized							Heat treated							
	C	Si	Mu	Ni	V	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
											Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1273	0.45	0.38	0.46	.....	0.33	71 000	79 300	107 100	22.0	55.2	208	24	85 000	95 400	115 300	11.7	45.3	196	27	380
1173	.38	1.35	.79	3.00	.30	51 000	87 300	145 300	16.0	46.9	255	38	130 000	.....	288 400	9.0	37.6	.....	43	121
23	.56	1.09	1.14	3.06	.21	.....	.....	.....	.....	.....	.....	.....	170 000	224 600	292 300	.1	3.4	512	69	123
1207	.60	1.30	.79	3.15	.32	83 000	103 200	139 000	19.5	48.4	302	26	.....	276 500	343 600	5.0	7.8	627	60	75
1271	.74	.....	.....	.....	.34	60 000	77 500	116 600	7.5	20.8	217	22	110 000	.....	150 900	2.3	31.0	340	40	91

TABLE 21.—Group M—Cobalt Steels

No.	Composition							Normalized						Heat treated							
	C	Si	Mn	Ni	Zr	Mo	Co.	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Brinell hardness numeral	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
																			Brinell	Scleroscope	
	P. ct.	P ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.		Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
22.....	0.37	0.92	0.69	2.21	0.25	.....	1.10	.....	.....	.....	.....	.....	.....	143 600	238 100	277 900	8.7	38.4	512	60	99
14.....	.43	1.56	1.08	3.01	.34	.....	.37	.....	.....	.....	.....	.....	.....	175 000	268 300	325 400	8.5	19.8	534	64	181
15.....	.43	1.28	1.09	3.45	.....	0.70	.38	.....	.....	.....	.....	.....	.....	140 000	.....	226 700[a]	(a)	(a)	509	70	72
3.....	.44	1.46	.90	3.06	.37	.27	.59	.....	.....	.....	.....	.....	.....	.....	229 500	288 600	7.8	26.2	589	69	.....

[a] Broke in shoulder.

TABLE 22.—Miscellaneous Steels

CHROMIUM-TUNGSTEN STEELS

No.	Composition								Normalized							Heat treated							
	C	Si	Mn	Ni	Al	Zr	Ti	Other elements	Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Proportional limit	Yield point	Ultimate strength	Elongation in 2 inches	Reduction of area	Hardness numeral		Impact
														Brinell	Scleroscope						Brinell	Scleroscope	
	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.		Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Lbs./in.²	Lbs./in.²	Lbs./in.²	P. ct.	P. ct.			Ft.-lbs./in.²
1177..	0.31	0.13	0.41	3.75	0.10	0.01	0.10	Cr—1.95, W—0.90	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1178..	.32	.14	.38	3.50	Tr.	.....	.....	Cr—2.00, W— .90	66 000	170 900	206 500	3.0	10.9	418	50	150 000	205 000	258 100	8.5	11.0	512	65	78
URANIUM STEELS																							
1244..	0.43	1.30	0.90	3.00	0.01	.....	.....	U—0.34	.....	133 500	183 500	6.0	12.9	289	35	150 000	195 000	309 800	10.5	35.2	627	73	102
1229..	.45	1.05	.75	3.00	.01	.....	.....	U— .36	.....	233 700	239 700	3.0	8.5	317	34	145 000	191 900	282 800	2.5	8.7	532	50	109
1228..	.63	1.20	.84	3.00	.01	.....	.....	U— .52	.....	169 100	176 400	.5	2.7	306	37	130 000	.....	299 800	1.0	3.4	622	61	37

VII. SUMMARY AND CONCLUSION

1. About 193 heats of steel, containing in various combinations the principal variable elements of carbon, silicon, nickel, aluminum, titanium, zirconium, cerium, boron, copper, cobalt, uranium, molybdenum, chromium, and tungsten, have been studied.

2. None of the steels presented any difficulties in rolling into plate except those containing boron.

3. The usual mechanical and impact tests were carried out on all of the steels. It is shown that steel containing 0.40 to 50 per cent carbon, 1 to 1.50 per cent silicon, 3 to 3.25 per cent nickel, and 0.60 to 0.80 manganese and deoxidized with a simple deoxidizer such as alumium can be produced having a tensile strength of approximately 300 000 lbs./in.^{2} with excellent ductility and toughness. This type of steel is recommended for structural material.

4. Although the same high properties are obtained in steels of the above composition with the aid of additional elements, it does not appear necessary to resort to such additions of more costly alloying elements.

5. Zirconium, like titanium and aluminum, acts primarily as a scavenger, and when it is not removed as part of the slag remains in the steel in the form of square bright-yellow inclusions not directly visible at magnifications lower than 500×. It is not considered that these inclusions can be very beneficial, and if they are segregated into groups and rolled out into thin platelike streaks they may be detrimental.

6. Of the other elements that are regarded as special alloying additions, chromium, tungsten, vanadium, and molybdenum go into solution and produce a martensitic pattern in the air-cooled specimens. Cerium and uranium act in a similar manner, but also show characteristic inclusions. Copper goes into solution, but a larger amount is required to produce a martensitic pattern in the air-cooled samples than for the others. Boron forms a complex eutectic, probably that of an iron-carbon-boron compound with iron. This eutectic is fusible at the temperatures ordinarily used in rolling, but at slightly lower temperatures steel containing boron can be rolled successfully. Hot working breaks up the eutectic, and spherical hard particles, similar to iron carbide globules, are formed.

VIII. ACKNOWLEDGMENTS

An investigation covering so many fields of work required the cooperation of many individuals. The authors consider that any merits the investigation may possess are largely due to their collaborators.

The development of the methods of chemical analysis was the contribution of Dr. G. E. F. Lundell, who, assisted by H. B. Knowles and part time by Ensign R. McLane, J. R. Eckman, and Miss E. R. Ward, also made the chemical analyses for the unusual elements. The rolling of the plates was mainly carried out by R. G. Waltenberg, assisted by R. D. France and W. M. Laughton. The last and F. C. Speidel assisted in determining the mechanical properties. Most of the heat treatment was done by H. R. Yerger and the microexaminations entirely by S. Epstein, and H. Scott was responsible for most of the results in thermal analysis.

WASHINGTON, March 30, 1921.

APPENDIX

THE DETERMINATION OF ZIRCONIUM IN STEEL [1]

By G. E. F. Lundell and H. B. Knowles

(a) PRELIMINARY STATEMENT

The method developed at the Bureau of Standards permits the determination of silicon, aluminum, titanium, and zirconium in one portion of the steel and provides for the following possible interfering elements: Tungsten, chromium, uranium, cerium, manganese, phosphorus, vanadium, molybdenum, copper, nickel, and cobalt.

(b) METHOD

Dissolve 5.00 g of the steel in 50 cc of hydrochloric acid (sp. gr. 1.2) with gentle warming and the addition of one cc portion of nitric acid from time to time to insure solution of the zirconium and titanium and also oxidation of the iron.

When solution is complete, evaporate to dryness, take up in 10 cc of hydrochloric acid (sp. gr. 1.2), again evaporate to dryness, and finally bake at a gentle heat in order to decompose nitrates. Cool, take up in 50 cc of 1 : 1 hydrochloric acid, and filter when the iron is completely in solution. Wash the residue with hot 3 per cent hydrochloric acid. Save the filtrate and washings.

Ignite the residue and paper in a platinum crucible, cool, and weigh. Treat with 1 cc of sulfuric acid (1 : 1) and sufficient hydrofluoric acid, fume off in the usual manner, ignite and weigh to obtain silica, and calculate silicon. Fuse the slight residue left after the hydrofluoric acid treatment with a small amount of potassium pyrosulfate, dissolve in 10 to 20 cc of 5 per cent sulfuric acid and add the solution to the acid extract from the ether separation obtained as described below.

Evaporate the filtrate and washings from the silica determination to a sirupy consistency, take up in 40 cc of hydrochloric acid (sp. gr. 1.1) and extract with ether in the usual manner. (The ether extract will contain most of the molybdenum, and this element may be qualitatively tested for in it. If molybdenum is present, it is more conveniently determined in a separate portion of steel.) The acid extract will contain some iron and all of the zirconium, titanium, aluminum, nickel, chromium, etc.

Gently boil off the ether in the acid extract, add the matter recovered from the silica, oxidize ferrous iron with a little nitric acid, dilute to 300 cc, cool, and precipitate with 20 per cent sodium hydroxide solution, adding 10 cc in excess. The sodium, hydroxide solution should be as pure as possible and free from carbonate. Filter and save the filtrate. Dissolve the precipitate in warm dilute 1 : 1 hydrochloric acid, repeat the sodium hydroxide precipitation, filter, and combine the sodium hydroxide filtrates. Dissolve the sodium hydroxide precipitate in warm dilute 1 : 1 hydrochloric acid and reserve the solution for subsequent analysis.

It is advisable to treat as follows the filter or filters used above: Ignite in platinum, fuse with sodium carbonate, digest the cooled melt with hot water, wash the residue, discard the filtrate and washings, dissolve the residue in hot 1 : 1 hydrochloric acid, and add to the main acid solution. This precaution makes certain the recovery of any zirconium held back on the filter as zirconium phosphate insoluble in acid.

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[1] J. Ind. and Eng. Chem., 12, p. 562; 1920.

Determination of Aluminum

(*a*) In the absence of chromium and uranium add a few drops of methyl red to the sodium hydroxide filtrate, neutralize with hydrochloric acid, add 4 cc of concentrated hydrochloric acid per 100 cc of solution, boil, make barely alkaline with ammonium hydroxide, continue the boiling for 3 minutes and set the beaker aside for 10 minutes. If no precipitate settles out, the absence of aluminum is assured. If a white precipitate settles out, aluminum is indicated. This precipitate is always contaminated by phosphorus pentoxide and must be purified as follows: Filter without washing, discard the filtrate, and dissolve the precipitate in warm 1:1 hydrochloric acid. Dilute the solution to 50 cc, make alkaline with ammonium hydroxide, neutralize with nitric acid, and add 2 cc in excess. Warm to 50° C, precipitate the phosphoric acid with molybdate reagent in the usual manner, filter, and wash the phosphomolybdate with an ammonium acid sulfate solution. Precipitate the aluminum in the filtrate as directed above, filter without washing, dissolve the precipitate in warm 1:1 hydrochloric acid, reprecipitate, filter, wash slightly with 2 per cent ammonium chloride solution, and ignite in a platinum crucible. The ignited residue is usually contaminated by silica. Therefore a sulfuric acid-hydrofluroic acid treatment, followed by ignition to alumina over the blast lamp, should be performed. (The sodium hydroxide reagent must be tested for substances precipitable by ammonia, and appropriate corrections must be made in the aluminum determination when these are present.)

(*b*) In steels containing chromium proceed as above until the filtrate from the molybdate precipitation is obtained. Then make the solution ammoniacal, oxidize with a little bromine water, make just acid with 1:2 nitric acid; add ammonium hydroxide in slight excess, heat to boiling, filter, dissolve the precipitate in dilute hydrochloric acid, and reprecipitate the aluminum hydroxide as directed above.

(*c*) In steels containing uranium the only modification which is required is the substitution of ammonium carbonate for ammonium hydroxide as the final precipitant of the aluminum hydroxide.

(*d*) In steels containing vanadium, alumina which is obtained by the above procedures from steels containing vanadium is contaminated by this element. When dealing with these steels, proceed as follows: Fuse the weighed residue with pyrosulfate, extract the cooled melt with 5 per cent sulfuric acid, reduce the vanadium in a Jones reductor having ferric alum in the receiver, titrate the reduced solution with standard permanganate, calculate the vanadium as V_2O_5, and subtract from the original weight.

Determination of Zirconium and Titanium

Dilute the hydrochloric acid solution to 250 cc, neutralize with ammonium hydroxide, so as to leave approximately 5 per cent (by volume) of hydrochloric acid, add 2 g of tartaric acid, and treat with hydrogen sulfide until the iron has been reduced. Filter if the sulfide group is indicated. Make the hydrogen sulfide solution ammoniacal and continue the addition of the gas for five minutes. Filter carefully and wash with dilute ammonium sulfide-ammonium chloride solution. Filter through a new filter if the presence of iron sulfide in the filtrate is indicated. Save the filtrate. (The sulfide precipitate consists of ferrous sulfide in addition to the greater part of any nickel, cobalt, and manganese present in steel. It is preferable to determine these in separate portions of the steel.)

Neutralize the ammonium sulfide filtrate with sulfuric acid, add 30 cc in excess, and dilute with water to 300 cc. Digest on the steam bath until sulfur and sulfides have coagulated, filter, wash with 100 cc of 10 per cent sulfuric acid, and cool the filtrate in ice water. Add slowly and with stirring an excess of a cold 6 per cent water solution of cupferron. (The presence of an excess is shown by the appearance of a white cloud, which disappears, instead of a permanent coagulated precipitate.) After 10 minutes filter on paper, using a cone and very gentle suction, and wash the pre-

cipitate thoroughly with cold 10 per cent hydrochloric acid. Carefully ignite in a tared platinum crucible, completing the ignition over a blast lamp or large Meker burner, cool, and weigh the combined zirconinum and titanium oxides. Fuse with potassium pyrosulfate, dissolve in 50 cc of 10 per cent (by volume) sulfuric acid, and determine titanium colorimetrically or volumetrically. Calculate titanium oxide, subtract the weight found from that of the combined oxides, and calculate zirconium.

(c) NOTES ON THIS METHOD

1. Phosphorous pentoxide contaminates the precipitate to so slight an extent that it can be disregarded.

2. Vanadium interferes no matter what its valency. The interference is not quantitative. If present in the steel, proceed as usual through the weighing of the cupferron precipitate. Then fuse thoroughly with sodium carbonate, cool, extract with water, filter, and determine the vanadium in the filtrate by adding sulfuric acid, reducing through a Jones reductor into a solution of ferric alum-phosphoric acid and then titrating with standard permanganate. Vanadium is thus reduced to V_2O_2 and then oxidized to V_2O_5. Calculate V_2O_5 and subtract from the combined oxides. Ignite in the original crucible the matter insoluble in water, fuse with potassium pyrosulfate and proceed as directed for titanium.

3. Tungsten does not interfere, since it is separated from zirconium and titanium by the sodium hydroxide treatment and from aluminum by the ammonium hydroxide precipitation. If tungsten is present in large amount it may be found desirable to fuse the nonvolatile residue from the silicon determination with sodium carbonate, extract with water, filter, dissolve the residue in hot 1:1 hydrochloric acid, and add to the acid extract from the ether separation.

4. Uranium is partially carried down when present in the quadrivalent condition, but not at all in the sexivalent state. If this element is suspected, boil out all hydrogen sulfide before the cupferron precipitation, oxidize with permanganate to a faint pink, cool, and proceed with the cupferron precipitation.

5. Thorium and cerium interfere, but they are not thrown down quantitatively. In case these elements are suspected the peroxidized solution used for the titanium determination must be quantitatively preserved and reduced with a little sulfurous acid. The rare earths are then separated by Hillebrand method,[2] as follows: Precipitate the hydroxides with an excess of potassium hydroxide, decant the liquid, wash with water once or twice by decantation, and then slightly on the filter. Wash the precipitate from the paper into a small platinum dish, treat with hydrofluoric acid, and evaporate nearly to dryness. Take up in 5 cc of 5 per cent (by volume) hydrofluoric acid. If no precipitate is visible, rare earths are absent. If a precipitate is present, collect it on a small filter held by a perforated platinum or rubber cone and wash it with from 5 to 10 cc. of the same acid. Wash the crude rare-earth fluorides into a small platinum dish, burn the paper in platinum, add the ash to the fluorides, and evaporate to dryness with a little sulfuric acid. Dissolve the sulfates in dilute hydrochloric acid, precipitate the rare-earth hydroxides by ammonia, filter, redissolve in hydrochloric acid, evaporate the solution to dryness, and treat the residue with 5 cc of boiling hot 5 per cent oxalic acid. Filter after 15 minutes, collect the oxalates on a small filter, wash with not more than 20 cc of cold 5 per cent oxalic acid, ignite, and weigh as rare-earth oxides which are to be deducted from the weight of the cupferron precipitate.

The above procedure does not give an absolutely quantitative recovery of the rare earths. Experiments indicate a recovery of approximately 85 per cent of the rare earths present in residues containing 100 mg of zirconia, 2 mg of thoria, and 2 mg of ceria. Attempts which were made to omit the preliminary separation of the rare earths, as fluorides, were unsuccessful.

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[2] U. S. Geol. Survey, Bul. 700, p. 176.

6. Instead of the prescribed treatment for the removal of the bulk of the iron, Johnson's [3] method of fractional precipitation with ammonium hydroxide may be used. When using this method, it is recommended that the 1:1 hydrochloric acid solution of the ammonium hydroxide precipitate should be further treated as given in the Bureau of Standards method beginning with "oxidize * * * and precipitate with a 20 per cent sodium hydroxide solution." In Johnson's procedure silicon must be determined in a separate portion.

7. After considering the method and studying the notes the reader might ask the question, "Why not use ammonium hydroxide instead of cupferron as the final precipitant?" The disadvantages of such a procedure are the following: (*a*) The necessity for destroying the tartaric acid which is in the solution, with attendant danger of contamination by material resulting from the attack on glassware; (*b*) the coprecipitation of phosphorus and also chromium and uranium when they are present.

The advantages of an ammonia precipitation are: (*a*) It is a cheaper reagent; (*b*) the precipitation of cerium would be complete instead of partial.

The following scheme of analysis is now being tested at this Bureau: Zirconium, titanium, aluminum, cerium, chromium, vanadium, etc., are first separated from the bulk of the iron by Johnson's method, and the hydrochloric acid solution of this precipitate is then treated with sodium hydroxide and sodium peroxide as described by Noyes, Bray, and Spear.[4] It is hoped that this treatment will quantitatively precipitate iron, zirconium, titanium, and cerium, leaving such elements as aluminum uranium, vanadium, chromium, tungsten, molybdenum, and phosphorus in solution. Iron, manganese, and the greater part of the copper, nickel, and cobalt are next separated by precipitation with ammonium sulfide in the presence of tartrate, as recommended by Thornton,[5] and zirconium, titanium (and cerium) are finally precipitated by ammonia after destroying the tartaric acid. The ignited and weighed precipitate is then treated for titanium and the rare earths as described in the Bureau method.

(d) CONFIRMATORY EXPERIMENTS

Below is given a summary of the data obtained in the analysis of the Bureau of Standards acid-open-hearth steel No. 20*a* to which definite amounts of standardized solutions were added.

No.	V present G	Cr present G	Cu present G	Ni present G	Al added G	Al found G	T added G	Ti found G	Zr added G	Zr found G
1	0.0005	0.0009	0.0034	0.0009	None	None	None	None	None	None
2	.0005	.0009	.0034	.0009	None	None	None	None	None	None
3	.0005	.0009	.0034	.0009	0.0100	0.0101	0.0100	[a] 0.0102	0.0101	[b] 0.0097
4	.0005	.0009	.0034	.0009	.0100	.0094	.0100	[a] .0102	.0101	[b] .0097
5	.0005	.0009	.0034	.0009	.0500	.0502	.0476	[c] .0482	.0500	[b] .0493
6	.0005	.0009	.0004	.0009	.0500	.0501	.0476	[c] .0482	.0500	[b] .0492

[a] Colorimetrically.

[b] The special treatment for vanadium (see note 2) was not carried out. This furnishes an interesting light on the slightly higher values for titanium obtained both colorimetrically and volumetrically and the correspondingly lower values for zirconium which resulted on account of the omission of this step.

[c] Volumetrically after reduction in a Jones reductor and collection in ferric-alum solution.

[3] Loc. cit.

[4] Technology Quarterly, 21, p. 35, 1908.

[5] Am. J. Sci., 87, p. 173, 1914.

The following modifications of the above method were employed by Lieut. R. McLane in the analysis of zirconium steels at the Ithaca station of the Bureau of Mines:

1. Treat the evaporated solution containing silica with 25 cc of hydrochloric acid (sp. gr. 1.2), again evaporate to dryness, bake and take up in 30 cc of hydrochloric acid (sp. gr. 1.2)+40 cc of water.

2. Ignite the insoluble residue and without weighing (silica being obtained on a separate sample by dehydration with sulphuric acid) add 2 cc of sulphuric acid (sp. gr. 1.84), an excess of hydrofluoric acid, and fume off the sulphuric acid. Dissolve the unignited residue in hydrochloric acid (1 : 1) and add to the acid extract from the ether separation.

3. Evaporate the filtrate from the silica determination to 25–40 cc volume, cool by placing in a larger beaker through which a stream of water is passed, and add 200 cc of ether. Stir, let settle, decant off ether, add 100 cc more ether, and repeat the operation. Perform a third extraction, if necessary, and pipette off the last of the ether, thus avoiding any transfer of the solution.

4. To separate aluminum, heat the oxidized solution to boiling and pour it with constant stirring into 135 cc of hot sodium hydroxide solution (20 per cent) contained in a 600 cc Pyrex beaker. After the precipitate has settled filter, allow the filtrate to stand overnight, and refilter if a precipitate appears. One extraction carried on as above is sufficient.

5. Place the filters and precipitates in the original beaker, add 25 cc of hydrochloric acid (sp. gr. 1.2), dilute to 125 cc, and heat. Filter off the insoluble, wash, ignite, fuse with sodium carbonate, and proceed as in the method.

6. Add methyl red and 8 cc of ammonia (sp. gr. 0.9) to the sodium-hydroxide filtrate, make slightly acid with hydrochloric acid, dilute to 500 cc, heat to boiling, and make just alkaline with ammonia. Let stand warm for one hour, filter, dissolve the precipitate in hydrochloric acid, and dilute the cooled solution to 100 cc volume. Take out exactly 10 cc for a Fe_2O_3 determination by the colorimetric thiocyanate method. Precipitate the remainder of the solution as above and proceed with the molybdate separation as in the method. Finally deduct nine-tenths of the blank (blank has had SiO_2 and Fe_2O_3 deducted and is usually negligible) and divide the weight of Al_2O_3 by 0.9, giving Al_2O_3.

7. Treat the ignited cupferron precipitate with an excess of sulphuric and hydrofluoric acids, evaporate, ignite, and weigh in order to correct for any silica present.

8. Dissolve the weighed precipitate in sulphuric and hydrofluoric acids, evaporate to fumes of sulphuric acid, and make up to definite volume. Determine TiO_2 in one aliquot portion by the colorimetric peroxide method and Fe_2O_3 in another by the colorimetric thiocyanate method and deduct.

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